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**DRIVE-BASED MODELING AND VISUALIZATION OF
CREW RACE STRATEGY AND PERFORMANCE**

by

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A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Industrial Engineering and Management Systems
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at the University of Central Florida
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ABSTRACT

Crew race strategy is typically formulated by coaches based on rowing tradition and years of experience. However, coaching strategies are not generally supported by empirical evidence and decision-support models. Previous models of crew race strategy have been constrained by the sparse information published on crew race performance (quarterly 500-meter splits). Empirical research has merely summarized which quarterly splits averaged the fastest and slowest relative to the other splits and relative to the average speed of the other competitors.

Video records of crew race world championships provide a rich source of data for those capable and patient enough to mine this level of detail. This dissertation is based on a precise frame-by-frame video analysis of five world championship rowing finals. With six competing crews per race, a database of 75 race-pair duels was compiled that summarizes race positioning, competitive drives, and relative stroke rates at 10-meter intervals recorded with photo-finish precision (30 frames per second).

The drive-based research pioneered in this dissertation makes several contributions to understanding the dynamics of crew race strategy and performance:

- An 8-factor conceptual model of crew race performance.
- A generic drive model that decomposes how pairs of crews duel in a race.
- Graphical summaries of the rates and locations of successful and unsuccessful drives.
- Contour lines of the margins that winning crews hold over the course of the race.
- Trend lines for what constitutes a probabilistically decisive lead as a function of position along the course, seconds behind the leader, and whether the trailing crew is driving.

This research defines a new drive-based vocabulary for evaluating crew race performance for use by coaches, competitors and race analysts. The research graphically illustrates situational parameters helpful in formulating race strategy and guiding real-time decision-making by competitors. This research also lays the foundation for future industrial engineering decision-support models and associated parameters as applied to race strategy and tactics.

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CHAPTER ONE: INTRODUCTION

Research Objectives

The development and application of industrial engineering decision-support models to assist in the formulation of crew race strategy and tactics has been hindered by a lack of empirical evidence on which these models could be based. Even at the highest levels of international competition, the measurement and official reporting of crew race results is limited to the quartile split times at the 500-meter points in a 2000-meter race. This data limitation has led to the analysis and interpretation of crew race strategy and performance in terms of simply categorizing the patterns of 500-meter splits.

A large body of published research suggests that rowing biomechanics, physiology, and race psychology interact with strategy and tactics at a level of granularity more detailed than 500-meter splits. Supporting this, personal accounts of crew races contain frequent references to “drives” that crews make against each other and the psychological effects of successful or failed drives on winning. Thus, the categorization of crew race performance based simply on 500-meter split data inadequately represents the actual strategy and tactics as planned and executed in crew races.

This dissertation addresses gaps in the literature that can be attributed to:

1. Insufficient physical observations as reported in official race results.
2. Suboptimal race models based on analyzing the fastest quartiles of the race rather than models based on analyzing situational behavior at the most decisive points of the race.

3. Not knowing what constitutes a probabilistically “decisive lead” as a basis for strategy decision-support and post-race performance analysis.

This study will methodically extract, decompose and model selected crew race physical criteria from video records of world championship crew races. This data will then be used to model situational performance and illustrate race strategy behavior including a categorization of tactical drives and relative positioning as probabilistic predictors of crew race performance. In so doing, this research will lay the foundation for extending the field of industrial engineering into the domain of racing strategy – in particular, crew race strategy, although many of the techniques piloted in this dissertation could similarly be applied to other types of athletic races.

The detailed information obtained in this research could someday drive a variety of new industrial engineering innovations applied to race strategy and performance research, including:

1. Decision-support models that guide coaches and racing competitors in goal selection and contingency planning. For instance, under what circumstances should crews shift their strategy from trying to catch the crew in front of them to holding off the trailing crews behind them? Such decisions can be guided by empirical evidence on the rates at which crews can drive on each other and the magnitude of leads that can be made up given the amount of time left in the race.
2. Physiological models that explore the what-if possibilities for the stroke rates and biomechanical gearing of the rigging as a function of race conditions and the expected fatigue levels of the crews. For instance, in a strong headwind, crews need to budget their energy usage over a longer race time. New models could

guide how much adjustment is needed and what would be the expected race pattern for competing crews that do not make an appropriate adjustment – possibly taking the lead early and then burning out late in the race.

3. Training simulation tools for coxswains to allow them to gain a situation awareness of expected and unexpected circumstances they may encounter in a race. Similar to airline pilots, coxswains should practice in training simulators for the decisions and tactics they may need to employ as unexpected situations occur in a race. Empirical research is needed to parameterize these simulation tools including the rates at which crews can be expected to drive on each other in a race. Coxswains need practice on the optimal real-time decisions to make in a race when circumstances deviate – better or worse – from the race plan.

Crew Race Concepts and Terminology

The standard crew race distance is 2000-meters. Distance markers are usually available at the 500-meter splits of the course. For international regattas, time splits are recorded at these 500-meter intervals, but for most lower-level races, only a finishing time is typically recorded for crews.

All crews begin their race with a start that is rowed at a higher stroke rate than the body of the race. Near the end of the race, crews usually call a sprint in order to finish at a higher stroke rate. The body of the race is normally rowed at 34-38 strokes per minute. Starts and Sprints are usually rowed at 40-46 strokes per minute. A typical start or sprint may last for 20 or 30 strokes, or roughly a distance of 250 meters, and time duration of 30 to 45 seconds.

Some common terms used in the sport of rowing are:

1. **Crew:** A team or group of rowers.
2. **Racing Shell:** The type of boat used in crew races.
3. **Rigger:** The apparatus on the side of the boat that provides the fulcrum for the oar.
4. **Eight:** A shell for 8 rowers each holding a single “sweep” oar, plus one coxswain.
5. **Scull:** A form of rowing competition where each rower pulls on two oars at a time.
6. **Coxswain:** The person who steers the boat and gives commands to the rowers.
7. **Catch:** The point at which the oar is first inserted into the water and the application of power can then begin.
8. **Catch a Crab:** When the blade gets stuck in the water, thus slowing the shell. In the case of a “full crab” the rower must completely let go of the oar, or risk being pushed by the oar handle overboard.
9. **Pacing or Stroke Rate:** The number of strokes taken per minute.
10. **Regatta:** An organized crew race, usually covering 2,000 meters.
11. **Big-10 (or 20 etc.):** A coxswain call to the crew to take a certain number of power strokes with the intention of making a drive on the other crews.
12. **Ergometer:** An indoor rowing machine.
13. **Lightweights:** Rowers eligible to compete in a lighter weight class.

For purposes of this dissertation research, some additional terms are defined:

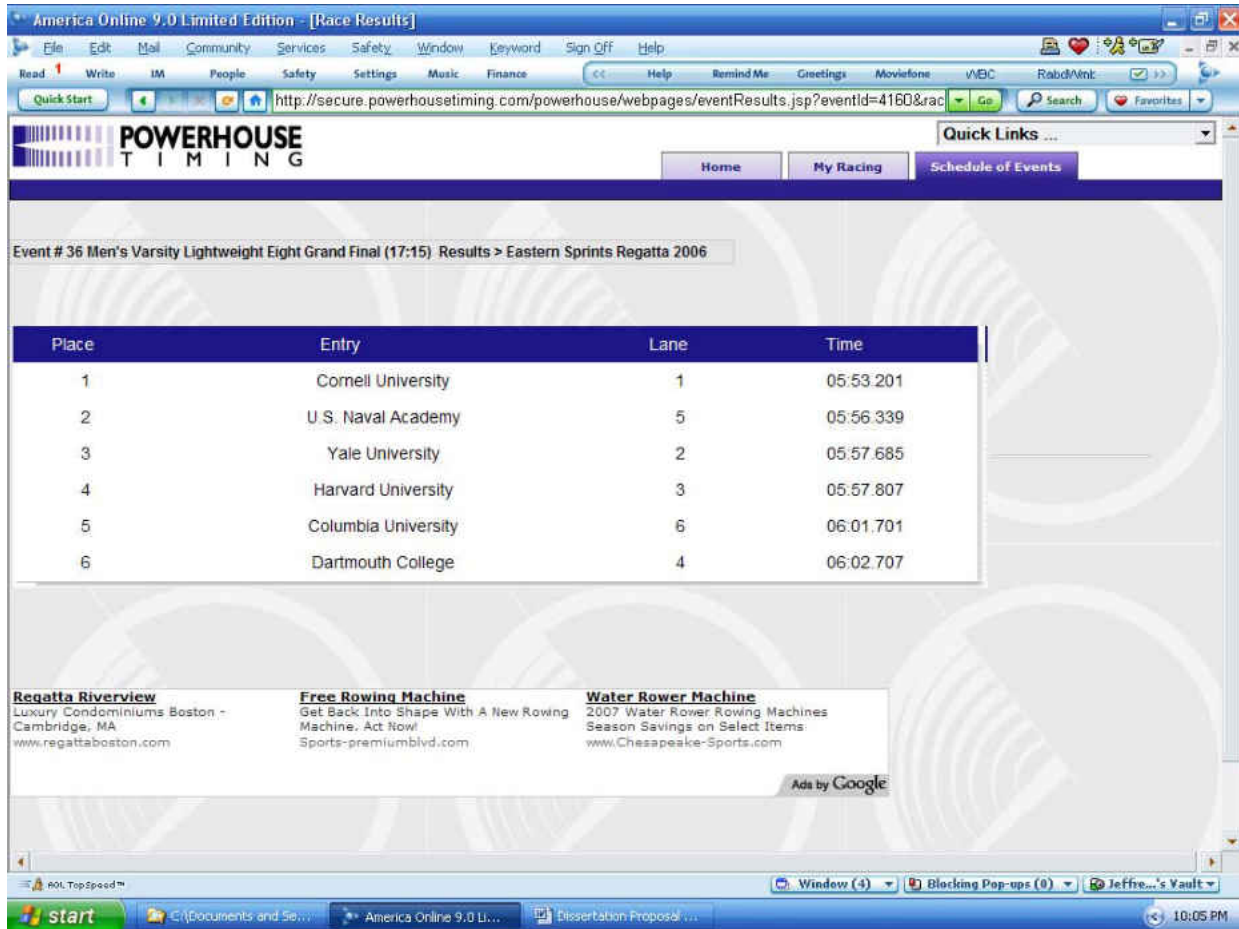
- **Blind Spots:** Portions of a race video record where not all crews are visible.

- **Drive:** A portion of the race where one crew is gaining on another crew, presumably due to the crew's own superior performance, but possibly due to the other crew fading.
- **Fade:** A portion of the race where a crew is falling back in comparison to other crews due to its own lagging performance. A fade may be due to exhaustion or a crew's morale being psychologically "broken" thus resulting in diminished effort and effectiveness.
- **Strategy:** A skillful plan to reach a goal. Strategy is the broad course of action the coach has set for winning – often characterized in terms of when the crew hopes or expects to take the lead. Crews that plan to take the lead early are pursuing an "early-lead" or "holding race" strategy. Crews that expect to trail early but gain the lead later in the race are pursuing an "even-paced" or "come-from-behind" race strategy.
- **Tactics:** The specific steps to implement race strategy. Common tactics include changing stroke rate pacing over the course of the race, and when or under what circumstances a crew takes a "Big-10" drive to move on other crews.
- **Race Plan:** The combination of strategy and tactics planned for the race including anticipated contingencies.
- **Contingencies:** Deviations from the race plan that are implemented by the coxswain during a race to react to actual race circumstances – sometimes unexpected and not anticipated in the race plan.
- **Performance:** The relative success of a crew in comparison to its competitors.
- **Quality of Execution:** How well the crew performed relative to its own plans and abilities. A well-executed race does not necessarily lead to a winning performance.

- **Duel:** A competition between two specific crews. In a 6-boat race, there are a total of 15 combinations of duels between different pairs of crews.
- **Position Duel:** The duels in a race that ultimately proved decisive in determining the final order of finish. In a 6-boat race, there are 5 position duels including three medal duels for first through third place.
- **Decisive Drive:** The drive in which the winner of the duel gained the final lead over the other crew, never to lose the lead afterwards.
- **Challenge Drive:** A drive by the losing crew in a duel possibly resulting in gaining a temporary lead or otherwise resulting in partially closing the lead of the winning crew.
- **Probabilistically Decisive Lead:** A lead of one crew over another crew (measured in seconds) that once gained, the crew can be confident of being able to hold this lead against the challenges of their opponent.

What is Typically Reported on Crew Race Results

Figures 1-1, 1-2, and 1-3 illustrate the level of granularity typically reported for championship races domestically and internationally.



Event # 36 Men's Varsity Lightweight Eight Grand Final (17:15) Results > Eastern Sprints Regatta 2006

Place	Entry	Lane	Time
1	Cornell University	1	05:53.201
2	U.S. Naval Academy	5	05:56.339
3	Yale University	2	05:57.685
4	Harvard University	3	05:57.807
5	Columbia University	6	06:01.701
6	Dartmouth College	4	06:02.707

Regatta Riverview
Luxury Condominiums Boston - Cambridge, MA
www.regattaboston.com

Free Rowing Machine
Get Back Into Shape With A New Rowing Machine. Act Now!
Sports-premiumblvd.com

Water Rower Machine
2007 Water Rower Rowing Machines Season Savings on Select Items
www.Chesapeake-Sports.com

Ads by Google

Figure 1-1: Collegiate Championship with No Split Level Data at All

The screenshot shows the World Rowing website interface. The main header features the 'WORLD ROWING.com' logo and a navigation bar with links for HOME, BIOGRAPHIES, RESULTS, STATISTICS, EXTRANET, and HELP. The page is titled 'Result search engine' and displays search results for the '2004 Olympic Games - Athens Schiras, Greece - Race 127 : M8+ / FA'. A table provides the 500-meter split results for the top six teams.

Rank	Boat	500 m	1000 m	1500 m	Finish
1	USA	01:21.95 (1)	02:48.18 (1)	04:16.95 (1)	05:42.48 (1)
2	NED	01:23.58 (5)	02:52.44 (5)	04:19.16 (2)	05:43.75 (2)
3	AUS	01:22.86 (4)	02:51.44 (2)	04:19.73 (3)	05:45.38 (3)
4	GER	01:22.48 (2)	02:52.14 (4)	04:23.22 (5)	05:49.43 (4)
5	CAN	01:22.70 (3)	02:51.70 (3)	04:21.44 (4)	05:51.66 (5)
6	FRA	01:25.84 (6)	02:55.67 (6)	04:25.48 (6)	05:53.31 (6)

Key to terms: DNA = Data Not Available - DNF = Did Not Finish - DNS = Did Not Start
DSQ = Disqualified - EXC = Excluded - BUW = Boat Under Weight

Figure 1-2: 2004 Men's Eights Olympic Finals with 500-meter Split Results

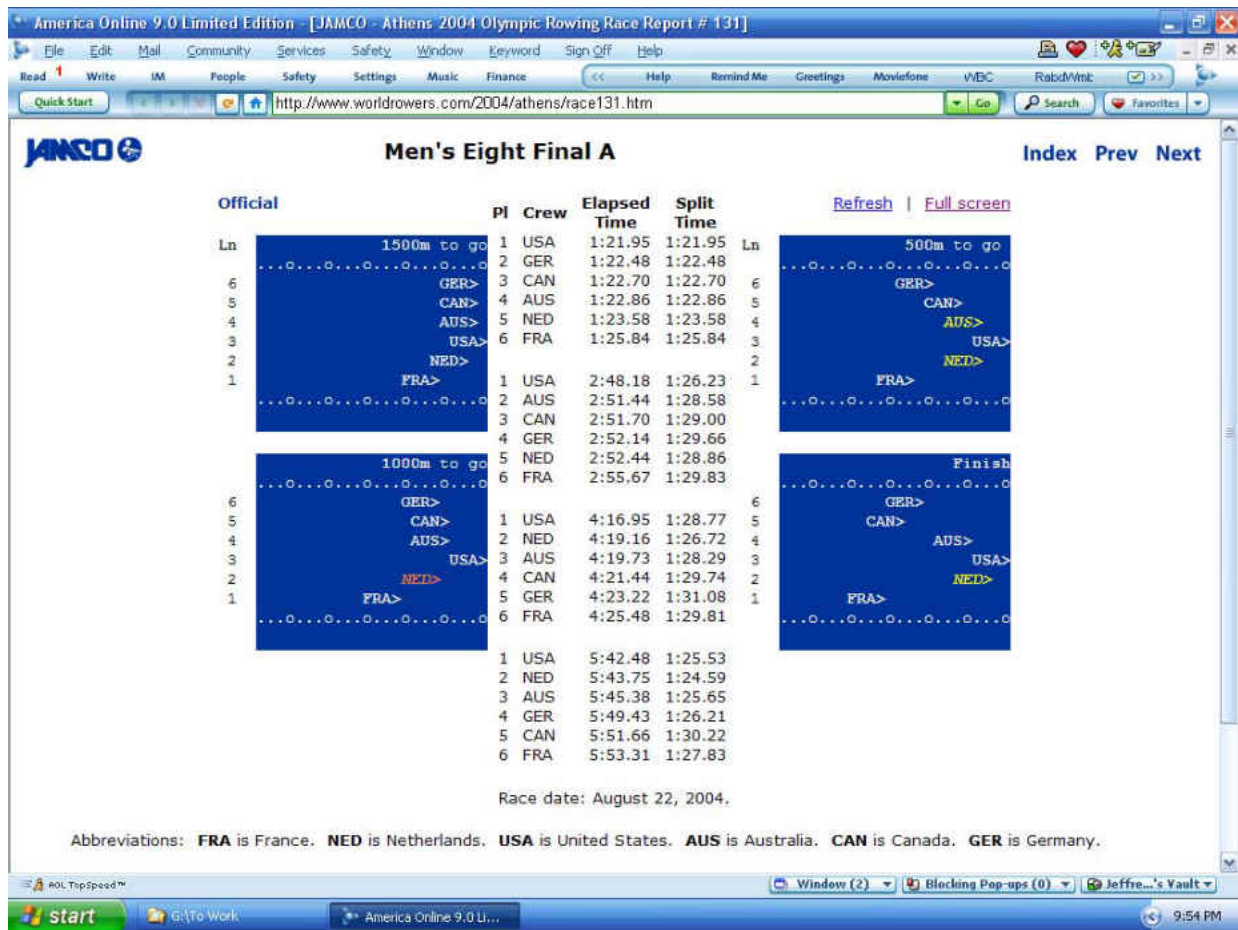


Figure 1-3: 2004 Olympic Finals with 500-meter Split Results and Graphics

Color Coding For Race Results as Illustrated by JAMCO:

Movements by crews during each 500 meter interval are highlighted by different colors. Gold (yellow) crews are closing on the leader in the current 500. Silver (light blue) crews are closing on the second place crew, but falling further behind the leader. Bronze (orange) crews are closing on the third place crew, but falling further behind the leader and the second place crews. White crews are falling further behind all three leading crews.

Research Hypothesis

This study will close a gap in the rowing research literature by exploring the general hypothesis that race strategy and performance can be more precisely modeled and illustrated based on the greater level of information detail that can be extracted from crew race video records. More specifically, the following hypothesis will be researched:

A methodological and detailed decomposition of selected crew race physical criteria can produce performance parameters useful in modeling situational performance and evaluating optimal strategies.

By modeling and illustrating crew race strategy and performance at a level of granularity down to 10-meter segments or 200 observed data points per race, drive-based analysis of crew race performance should produce evidence and insight into a wide range of racing issues, including:

1. Can video data be mined as a valuable source of crew race performance data?
2. Can drives be statistically analyzed and graphically displayed?
3. When are the winning drives made in races?
4. How well does the timing of drives correspond to 500-meter splits?
5. Do crews vary their stroke rates when taking a drive?
6. How often do winning crews pull steadily away from the other contenders for the entire length of a race?
7. Do crews tactically respond to the challenge of a crew driving on them?
8. Do crews hold back and adopt a conservative strategy when a win seems assured?
9. Are under-stroking crews more likely to make a drive late in a race?

10. Do crews “save up” their energy just before taking a Big-10 or sprint?
11. How much different do crews perform during race starts and race ending sprints?
12. Can losing crews be broken, resulting in a fade or total collapse late in the race?
13. What factors influence the probability of coming from behind to win?
14. Is there a practical limit to the amount of distance a trailing crew can hope to make up?
15. Under what circumstances would a crew’s optimal strategy shift from trying to catch the crews in front of them, to trying to hold off the crews behind them.
16. What kinds of race scenarios do coxswains need to be trained in how to respond?

Research Approach

The overall research goal of this dissertation is to model and visualize the drives crews make on each other that reflect the strategies used and the performance achieved in world class competitions. This requires methodically extracting, decomposing and modeling selected crew race physical criteria from video records of world championship crew races. This will close a gap in the rowing research literature due to the limited interpretations possible from studying only the four observation points corresponding to 500-meter splits reported on world championship races.

The public availability of video recordings of major international championships makes possible very detailed race analysis. Video analysis of a 6-minute race recorded at 30 frames per second provides 10,800 observation points. Unfortunately, the different camera angles used in a video race recording create “blind spots” that limit the number of observations possible for the different crews. Nevertheless, thousands of meaningful observations are possible from video analysis and at levels of precision of 1/30th of a second.

In this dissertation, the following steps are accomplished:

1. An overall conceptual 8-factor model of crew race performance is proposed based on the body of rowing research literature. Using this 8-factor model to guide a literature review, the scientific basis is established for how the principles of rowing biomechanics, physiology, and race psychology interact to form the foundation for racing strategy and tactics.
2. A software tool (EEVA) is developed for Extracting, Extrapolating, Visualizing, and Analyzing the detailed race information observable from a crew race video recording.

3. Detailed data is extracted from video records of five world championship races.
These five races include a total of 75 duels. For each crew in each of these races, times and stroke rates are further extrapolated into 10-meter intervals and compiled into a database.
4. A generic drive model is formulated to categorize the pattern of drives dueling crews may make on each other as they try to gain the lead or hold off their opponent.
5. Race results are analyzed to measure and illustrate the pattern of drives crews make on each other.
6. Parameters are measured as to what constitutes a probabilistically decisive lead in a duel as a function of position along the course and whether the trailing crew is driving on the leader.
7. Video-based measures of a probabilistically decisive lead are validated by performing the same calculations on a larger dataset of the officially reported race time splits.

*Low-information designs are suspect;
what is left out,
what is hidden,
why are we shown so little?*

Edward Tufte
(Tufte, 1983, p.168)

CHAPTER TWO: LITERATURE REVIEW

Until recently, there were no models in the literature that offered a unified theory of all of the factors that influence race strategy and performance. A comprehensive 8-factor conceptual model has recently been proposed to guide the evaluation of crew performance in actual races (Cornett et al, 2008). This literature review will explain the background behind this model, and then apply this model to reviewing the published research that serves as a foundation for understanding crew race strategy and tactics.

Toward An Overall Model of Crew Race Performance

Hundreds of research articles have been published on specific aspects of rowing biomechanics, physiology, psychology, anthropometrics, rowing style, equipment, and training. Numerous books have also been published containing personal accounts of racing experiences and interpretive details of what were the determining factors in these races. However, very few research studies have been done on the overall relationships of race strategies to performance results, and the studies that have been done are constrained by the fact that race results are only measured and reported based on quarterly 500-meter race splits. Garland (2005) shows how average velocity varies over the four quartiles. Kleshnev (2001(1)) shows the pattern of quartiles where winning and losing crews did their best and worst relative to their competitors.

Various researchers (including Zatsiorsky and Yakunin, 1991; Soper and Hume, 2004; and Atkinson, 2001) have developed biomechanical models to mathematically forecast boat speed as a function of the physics of racing cadence, force vectors, shifts in mass and

momentum, and hydrodynamic resistance. Such models are useful to study the theoretical efficiency of energy usage, but ignore the human factors of the race competitors – including skill, level of exhaustion, and psychological motivations. Computerized biomechanical models are deterministic in that they do not consider the uncertainties of race scenarios, intended strategies, the qualitative aspects of race day performance, and the situational aspects of how crews respond to their race positioning.

Other taxonomies in the literature categorize the research available on the sport of rowing. The US Rowing Association, the national governing body of the sport in the United States, has a web site that categorizes their archive of rowing literature (US Rowing Resource Library, 2008). Their taxonomy (see Table 2-1) includes 33 categories including mechanics, physiology, training, and race psychology, but also many other categories involving organizational governance and administration. This collection of documents is an archive of topics of interest including almost any subject related to race strategy and performance, but is not a cohesive model of how all the pieces fit together.

Table 2-1: US Rowing Resource Library (US Rowing Resource Library, 2008)

Primary Topic	Secondary Topic
1. Governance	By-laws, Code of Conduct, Constitution, Harassment, Personnel
2. Program Management	Communications, Constitution, Incorporation, Media, Newsletters, Open Water, Starting A Program, Structures, Support Groups, Tax Exempt, Volunteers
3. Coaching	Coxswains, Legal Issues, Masters, Methodology, Organization, Roles, Safety, Styles, Technique, Training, US Rowing, Youth
4. Officiating	Directory, Duties, Equipment, NASO, Rules, Starting, Training
5. Coxswains	Commands, Drills, Duties, Equipment, Motivation, Racing, Safety
6. Rowing Technique	Body Positions, Coaching, Common Errors, Drills, Finish, Oar, Rough Water, Sculling, Starting, Steering, Sweep, Training
7. Mechanics	Bio-mechanics, Drills, Physics, Style, Velocity
8. Physiology	Aerobic, Anaerobic, Alternative Training, Back, Energy Systems, Hydration, Hypo-hydration, Injury, Knee, Measurements, Metabolic, Muscles, Oxygen, Testing, Training
9. Flexibility	Examples, Implementation, Techniques
10. Training	Aerobic, Altitude, Anaerobic, Endurance, Energy Systems, Erg, Flexibility, Hypoxia, Jet Lag Effects, Masters, Olympic Athletes, Oxygen, Planning, Programs, Resistance, Speed, Strength, Testing
11. Injuries	Asthma, Back, Common Injuries, Epilepsy, Hands, Joint, Knee, Muscle Cramps, Neck, Over Training, Prevention, Treatment, Youth, Other
12. Nutrition	Carbohydrates, Competition, Diets, Disorders, Fat, Gaining Weight, Hydration, Lightweight, Losing Weight, Measurement, Performance, Pre-competition Meals, Protein, Re-hydration, Recommendations, Strength, Training, Vegetarians, Vitamins
13. Testing and Evaluation	Anaerobic, Approaches, Drug, Energy System, Measurement, Physiological, Stress
14. Racing	Psychology, Starts, Strategy
15. Psychology	Attention Skills, Burnout, Competition, Elite Athletes, Mental, Performance, Strategies, Stress, Visualization
16. Equipment	Building, Care, Classification, Docks, Maintenance, Oars, Pitchmaster, Rigging, Safety - PFD, Seats, Selection, Stretchers, Stroke Watch, Transportation

Primary Topic	Secondary Topic
17. Regattas and Events	Calendar, Course Construction, Entry Packets, Indoor, Organizing, Progression, Regatta Watchers, Registered Regattas, Rules
18. Masters Rowing	Aerobic, Endurance, Handicaps, Injuries, Psychology, Training
19. Women in Rowing	Endurance, Gender Equity, Menopause, Menstrual Cycle, Performance, Pregnancy, Working
20. Adaptive Rowing	Behavior, Blind, Physical, Programs, Special Olympics
21. Youth Rowing	Colleges, Heart Rate, Motivation, Programs, Starting, Stereotypes, Strength, Training
22. Recreational Rowing	Equipment, Programs, Training
23. Safety	American Red Cross, Capsizing, Cold, Heat, Hypothermia, Log Book, PFD Requirements, Practices, Swim Test, Traveling
24. Sponsorship and Fundraising	Examples, Junior, Organizing, Regatta
25. Boathouses	Building, Organizing, Storage, Winterizing
26. History of Rowing	American, Clubs, Collegiate, Olympics, USRowing Events, Women
27. Rowing Clubs, Camps and Schools	National Team, Schools, Summer Camps
28. Open Water Rowing	Racing, Touring, Training
29. Aesthetics	Photography
30. Minorities	Inner City, Stereotypes
31. Insurance	Organization, Shell, Waiver
32. National Team	Camps, Selection Procedures, Speed Orders, Testing Protocol, Testing Results, Trials
33. F.I.S.A.	Calendar, Federations, Rules

The tables of contents from books on rowing have similar shortcomings as to defining a cohesive, overall model of crew race performance. Although they categorize a range of interests for those who wish to learn more about the sport of rowing, their chapters are not organized so as to define an integrated model of rowing performance.

Perhaps, the most comprehensive book on the science and strategy of rowing is Rowing Faster (Nolte, 2005). It offers an anthology of advice from its contributing authors. There are

over 160 publications referenced in its bibliography. Parts 1 and 2 from the Table of Contents (Table 2-2) show coverage of physiology, biomechanics, rigging, rowing technique, and training. Part 3 adds advice on crew selection, the coxswain role, and racing. The components of an overall model of crew race performance are variously covered throughout this book, but an integrated model is not proposed.

Table 2-2: Table of contents from the book, Rowing Faster (Nolte, 2005)

<ul style="list-style-type: none"> • Part 1: Training <ul style="list-style-type: none"> Chapter 1. The Art of Rowing Chapter 2. Rowing Physiology Chapter 3. Monitoring Athletes Physiology Chapter 4. Managing Rowers' Medical Concerns Chapter 5. Developing an Aerobic Base Chapter 6. Improving Anaerobic Threshold Chapter 7. Sprint and Speed Work Chapter 8. Building Strength Chapter 9. Designing Your Training Plan
<ul style="list-style-type: none"> • Part 2: Technique <ul style="list-style-type: none"> Chapter 10. Rowing Biomechanics Chapter 12. Rigging Chapter 12. Bladework Chapter 13. The Catch Chapter 14. Leg Drive Chapter 15. Recovery Chapter 16. Inside the Rower's Mind Chapter 17. Ergometer Technique Chapter 18. Technology for Technique Improvement
<ul style="list-style-type: none"> • Part 3: Racing <ul style="list-style-type: none"> Chapter 19. Selecting Athletes and Crews Chapter 20. Setting Race Plans and Tactics Chapter 21. Relaxing and Focusing on Race Day Chapter 22. Coxing

Application of an 8-Factor Model of Crew Race Performance

Rowing has been very broadly researched through the examination of isolated topics. As yet, no unified model or theory is widely accepted as an overall theory of crew race performance. However, a generalized conceptual model of crew race performance has been recently proposed (Cornett et al, 2008). This literature review begins with this proposed overall conceptual model of crew race performance (Figure 2-1). Each of the eight model components are discussed building upon the available literature on the subject. The literature review will test the usefulness of this model by exploring how the principles of rowing biomechanics, physiology, and race psychology interact with racing strategy and tactics.

These eight factors can be further grouped into four macro-categories:

- **Base Capability** defines the raw talent of a crew and their capabilities in using their equipment. It includes the two factors for Human Talent (**H**) and Biomechanics (**B**).
- **Race Scenario** defines the circumstances a crew faces on race day. It includes the two factors for the crew's Physiology (**P**) and the Weather and Environment (**W**) on this particular day.
- **Performance Execution** is how well a crew actually performs relative to its base capability and the race scenario. It includes factors for the Quality of Execution (**Q**) and the effects of Race Psychology (**R**).
- **Decisions** made before and during a race also affect the race outcome. These include the coach's pre-race Strategy and Race Plan (**S**) and the coxswain's actual within-race application of Tactics and Contingencies (**T**).

Putting this all together, the performance of a crew in any given race is a function of the base capability of the crew when faced with a particular race scenario, combined with their performance execution of the decisions made before and during the race. This is a complete conceptual model of a crew's performance. Each of these factors interacts with each other on race day in a complex way. Due to uncertainties, the results of a future race cannot be predicted, yet the results of past races can be studied and evaluated.

A finished crew rows with such smoothness, ease, and precision that it all looks very simple. It is not until one looks beneath the surface and studies the factors that have combined to produce the finished product, that one realizes why it is that there is no study in the realm of college athletics so interesting, and very few so complicated, as boat racing.

Charles Courtney
(Young, 1923, p.96)

Model of Crew Race Performance

$$\text{Time} = f_{\text{split} = 1-n} (\mathbf{H} + \mathbf{B} + \mathbf{P} + \mathbf{W} + \mathbf{Q} + \mathbf{R} + \mathbf{S} + \mathbf{T})$$

where n = 1, 2, 4, 8, 20, 40, 200, or 10,000

Base Capability:

H = Human Talent

Anthropometrics, age, gender, health, talent and experience

B = Biomechanics

Equipment, ergonomics, mechanics, kinematics and rowing style

Race Scenario:

P = Physiology

Training and fitness, race distance, fatigue, energy expenditure and pacing

W = Weather and Environment

Water, wind, temperature, turns, lane fairness, random interventions

Performance Execution:

Q = Quality of Execution

Strategy execution, performance errors, steering, synchronization and swing theory

R = Race Psychology

Race importance, morale and character, motivation and effort, concentration and focus

Decisions:

S = Strategy and Race Plan

Coach: Competitive assessment, goals and planned contingencies, rigging, pacing, drives

T = Tactics and Contingencies

Coxswain: Situation awareness, options and risk assessment, pacing, drives, communication

Figure 2-1: An 8-Factor Overall Model of Crew Race Performance

Base Capability: Human Talent (H)

The human talent of a crew is a function of anthropometrics, age, gender, health, and athletic experience. This base capability defines how fast a crew should be able to perform if well trained and conditioned to race. Talent and experience also defines the reliability of how well the crew should perform on a consistent basis.

A common phrase used in sports is that “you cannot coach size.” It is as true for rowing as in other sports such as basketball where size is an obvious advantage. Although a model of crew race performance includes many other parameters, size and other anthropometric aspects of biomechanical advantage are natural differentiators of crew performance.

International rowing competitions are classified (US Rowing Referee Committee, 2008) according to boat type (number of rowers in the shell), gender, lightweight versus heavyweight (referred to as “openweight” for women’s competition), age, and experience level.

Men’s lightweight crews must average no more than 70 kg. (154.32 lbs.) per oarsman with a maximum individual weight of 72.5 kg. (159.84 lbs.). Women’s lightweights are limited to an average of 57 kg (125.67 lbs.) per rower with no individual rower weighing over 59 kg. (130.07 lbs.).

Elite men’s heavyweight crews average much heavier than women’s openweight crews (Nolte 2005). Male elite heavyweight oarsmen average 95 kg compared to 85 kg for elite openweight women. Elite men are also taller by a margin of 197 cm. to 185 cm.

Percent body fat is another differentiator between men versus women. Nolte offers a guideline for elite competitors that men’s body fat should not exceed 8 percent whereas women’s should not exceed 14 percent.

The combination of height, weight and body fat percentage substantially define body cell mass (muscles, brain, and inner organs) – about 52 percent for elite male heavyweights (Nolte, 2005). Of this, 85 percent is muscle mass, and 75 percent of this muscle mass is used in rowing. Because body cell mass is determined by body growth and training, younger competitors are at a disadvantage – until about age 19 (Nolte, 2005).

Although size is a source of competitive advantage in rowing, carrying extra weight can also be a competitive disadvantage. The rowing shell supports the weight of the rowers, so the weight disadvantage is caused by the extra hydrodynamic drag due to the racing shell sitting lower as it moves through the water. The manufacturers of the Concept ergometer offer a formula for adjusting ergometer performance scores for the effect of a rower's weight (Concept, 2007):

$$\text{Corrected Time} = \text{Actual Ergometer Time} \times \left(\frac{\text{Pounds Body Weight}}{270 \text{ lbs.}} \right)^{.222}$$

Any extra weight in the shell is a source of competitive disadvantage. Consequently, manufactures of shells, rigging, and oars are always seeking to use lighter composite materials.

For purposes of shell propulsion, coxswains are dead weight in the boat. Therefore, it is an advantage to carry as light a coxswain as possible. Consequently, for the sake of fairness and health reasons, coxswains in elite regattas are restricted to a minimum weight and must add deadweight to achieve the minimum. For international races (FISA Rules, 2007), coxswains for men's races must weigh a minimum of 55 kg. (121.25 lbs.), and for women's races the minimum is 50 kg. (110.23 lbs.).

The effect of size and gender on rowing performance is easily seen in championship race performance times. Kleshnev (2006) studied the results of World and Olympic championships from 1993 to 2004 according to the various boat classes. Kleshnev filtered out the best and worst times because they were presumed to have been significantly affected by weather conditions. Comparing the percentage difference in the average winning times, the expected variations by gender (M vs. W) and by weight class (L for Lightweight) can be calculated (Table 2-3).

For the 5 classes of Olympic events common to both genders, the average winning time for women averages 10.2% greater than for men. For the 3 classes of lightweight events, their winning times average 2.6% greater than their heavyweight (or openweight) counterparts.

Table 2-3: Average Variation in World Championship Winning Times

M8+	W8+	% of Best			
338.6	377.6	111.5%			
M4x	W4x	% of Best		M4-	LM4-
351.6	385.1	109.5%		354.4	362.5
				% of Best	% of Best
				102.3%	102.3%
M2x	W2x	% of Best		M2x	LM2x
374.3	411.2	109.9%		374.3	383.0
				% of Best	% of Best
				102.3%	102.3%
M2-	W2-	% of Best		W2x	LW2x
384.6	425.3	110.6%		411.2	424.5
				% of Best	% of Best
				103.2%	103.2%
M1x	W1x	% of Best			
405.2	444.5	109.7%			
M vs W Average:		110.2%		H vs L Average:	102.6%

Performance differences by gender and size has also been studied through ergometer experiments (Yoshiga and Higuchi, 2003). Using multiple regression, rowing performance is

shown to correlate with height, body mass, fat-free mass, and VO_{2max} . Male rowers outperformed female rowers, but the expected variation by gender was reduced to only about 4% when adjusting for differences in size and aerobic capacity. Other factors suggested to explain performance differences by gender include haemoglobin concentration, testosterone levels, and the relative size of leg muscles.

Besides anthropometric and physiological advantages, differences in human talent can also be attributed to rowing capacity and skill factors (Smith and Spinks, 1995). Discriminant function analysis was performed on ergometer results comparing novice, good, and national level rowers. The most powerful predictor was propulsive power per kilogram of body mass. Other significant predictors included the skill factors of stroke-to-stroke consistency, and stroke smoothness. Because power and skill levels can be correlated with experience categories, having experienced rowers improves the reliability of a crew to perform consistently well.

In an overall model of crew race performance, the quality of execution is treated as a separate factor in determining how well a given crew performs in any given race. Nevertheless, size, gender and other anthropometric advantages provide an expected base line of crew performance. These anthropometric advantages can also be factors of intimidation that can affect race psychology and race plan strategy.

*It's easy to get good players.
Getting them to play together, that's the hard part.*

Casey Stengel

Base Capability: Biomechanics (B)

The base capability of a crew is also a function of rowing technique and how well the crew uses and interacts with its equipment. In recent decades, the sport of rowing has been extensively studied using biomechanical techniques driven largely by new instrumentation technology and a growing interest in sports biomechanics. As described by Nolte (1991), biomechanics is interested in how the rower converts physiological capacity into moving the boat. Biomechanical considerations include ergonomics, kinematics and rowing style. Superior equipment can also be a contributing factor in winning a race. Crews respond well and perform better when they use better equipment, have it optimally rigged to fit them well, and are well trained in how to use their equipment.

Ergonomics and Equipment

A clear example of ergonomics applied to rowing is the relatively new initiative to offer competition adapted to physical handicaps. In 2002, the Federation International Society d'Aviron (FISA) introduced paralympic rowing to the world championships. This includes four boat classes adapted to different types of disabilities. These classes include men's and women's arms only single scull, mixed gender trunk and arms double scull, and mixed gender legs, trunk and arms coxed four events (FISA Adaptive, 2008).

Adaptive boats are ergonomically equipped with special seats that vary according to the disability of the rower. Three of the four events include fixed seats (versus sliding seats) to accommodate those without use of their legs. Other events provide special seats that afford

postural support to those whose sitting balance is compromised. Smaller boats are equipped with pontoons to provide additional lateral balance.

Ever since the sport of crew originated in the 19th century, the designs of equipment manufacturers have continually evolved to better accommodate the ergonomics of rowing, to maximize the mechanical advantages of equipment designs, and minimize the hydrodynamic drag from the shell and oars impacting the water. Over time, equipment has become lighter yet stiffer through the use of composite materials instead of wood.

One of the first major innovations was the introduction of the sliding seat between 1857 and 1861. The sliding seat allows the legs to be used as the primary form of propulsion. The timing of force application by the legs, arms and trunk, along with the dynamics associated with shifts in mass-momentum, results in a distinct profile of shell speed and the associated forces over the duration of the stroke (Jones and Miller, 2002).

Racing shells have been adapted in hull geometry design (Tuck and Lazauskas, 1996) to better fit the varying sizes of crews, water displacement and the associated hydrodynamics. Water resistance can be categorized into hull, pitch and skin resistance (Soper and Hume, 2004). Hull resistance (determined by shell design) accounts for about 8% of overall resistance. Pitch resistance (due to changes in vertical and horizontal orientations) accounts for about 4% of the total. Skin friction represents 88% of the water resistance to boat propulsion.

Oar blades have been redesigned to better catch the water, improve the quality of rowing bladework, and minimize negative hydrodynamic effects. In 1991, the asymmetrical “hatchet” blade was introduced. Some of the reported benefits of the hatchet blade (Soper and Hume,

2004) include more stability with less vertical movement, greater peak compressive force at the catch, and less slippage of the blade at the catch.

Outriggers have become increasingly adjustable to allow them to be individually adapted to fit each rower and accommodate diverse rowing styles including the quality of an individual's bladework. Rigging can also be adapted so as to raise or lower the oar blade relative to the water, thus better adapting to the wave height on race day.

Rigging that is well-adapted to the rower's anthropometrics enables advantages to be maximized (Barrett and Manning, 2004). Successful larger rowers have rigging that is well adapted to their body dimensions. However, the particular style of rigging adaptation in itself is not as strong a determinant of success as the size and strength of the rowers themselves.

Rigging adjustments allow the mechanical loads or "gearing" to be adapted to the expected race duration (affected by weather conditions), race strategy and stroke rate pacing. Rigging provides a fulcrum for mechanical advantage with the blade anchored in the water while force is applied to the oar handle. Adjusting the placement of the oar button (where the oar locks into the rigging) controls the ratio of mechanical leverage, and thus the mechanical work accomplished with each stroke. Force is also applied to the foot stretcher which also mechanically transfers into propulsion.

Kinematics of the Rowing Stroke

The rowing stroke can be defined in terms of four phases (catch, drive, finish, and recovery) in which different muscle actions are activated in a coordinated sequence (Mazzone, 1988). The drive phase can be further subdivided into a sequence where the emphasis is on legs,

body swing, and arm pull-through. Similarly, Kleshnev defined and illustrated the force dynamics of the drive in terms of six micro-phases beginning with the catch and ending with the release (Kleshnev, 2002).

Rowing style affects the performance of a crew. Crews vary considerably in the kinematics of rowing style according to the beliefs of their coaches and the difficulty of training rowers to conform to a common style. Biomechanical research seeks to reconcile these different styles based on scientific principles. The amount of biomechanical research is diverse and extensive. Sometimes the principles conflict with each other, adding to the divergence of views as to the ideal rowing style. A review of the rowing biomechanics literature (Soper and Hume, 2004) revealed evidence to support several commonly held beliefs:

- Higher stroke rates and longer drive lengths result in greater average boat velocity. However, it is difficult to do both simultaneously, so crews must fundamentally choose between these two in their rowing and racing style.
- Drive to recovery ratios are strongly negatively correlated to stroke rate and average boat velocity. Therefore, increases in stroke rate and velocity are primarily associated with speeding up the recovery phase of the stroke.
- Rowers of different ability levels can be distinguished by elements of both power and skill – including power per kilogram of body mass, propulsive work consistency, stroke to stroke consistency, and stroke smoothness.
- As stroke rate increases, peak oar force occurs earlier in the drive phase. The ability to maintain peak oar force through the middle of the stroke may also be an indicator of performance level.

- Greater force on the oar handle is generated when the elbows are extended at the start of the drive, and also when the elbows are kept close to the trunk at the finish.
- A sequence of power using first the lower limbs, then the trunk, and finally the arms may be a more effective rowing stroke for achieving greater boat velocity.

Aside from applying force to the oar, a rower also must move his own bodyweight horizontally and vertically during a stroke. Only 75% of the power is used to pull the oar (Nolte, 1991), whereas 9% is used to support horizontal body movement and 16% is used for vertical body movement. Nolte's research leads him to recommend four biomechanical principles as a framework for rowing technique:

1. All movements have to be performed in a way that the rower is able to transfer his/her physiological performance into optimal propulsion.
2. The long stroke is necessary to produce a high level of rowing performance.
3. The movement of the rower has to be as horizontal as possible so that the vertical displacement of the center of gravity is minimized without losing length in the stroke.
4. The horizontal velocity of the rower relative to the boat should be as small as possible. In other words, the displacement of the center of gravity in the horizontal plane should be minimized without losing length in the stroke, and there should be no lost time with stops or pauses.

Elements of rowing style include the positioning and relative motion of arms, back and legs over the duration of a stroke including the catch, drive, release, and recovery. The use of the

hands controls the height and angles of the oar and blade relative to the water in each of these phases. The kinematics of oar angles, shifts in mass momentum and the distribution of kinetic energy over the duration of the stroke have been well researched and illustrated (Kleshnev, 2002). Kleshnev's findings lead him to advocate that coaches and researchers should focus on what it takes to "move the rowers" as opposed to moving the boat. He advocates that rowing style should emphasize acceleration of the rower's body mass through the drive by applying force to the foot stretcher rather than just thinking of pulling on the oar. He also reminds rowers to make sure they cover the oar blade with water before making this push.

Timing of Force Application

The timing of force application during a stroke can vary according to coaching philosophy. Because a hard catch can cause the boat to check, some coaches believe a more gradual catch (resulting in some degree of slippage through the air as the oar enters the water) is a better rowing style. This is because it minimizes the slowing of the boat due to inefficient splashing of the water, and it also minimizes the extra vertical vector of energy needed to insert the oar quickly.

Other biomechanical principles favor application of power associated with a quick catch and a steep rise to maximum power at the start of the stroke (Schwanitz, 1991). His empirical research on boat speed compared to rowing style supports increased power emphasis on the early part of the drive. The position of the body in the early part of the drive is similar to that of a weightlifter at the beginning of a lift. Schwanitz interprets this position as allowing for a more synchronous whole-body effort incorporating leg, back and arm muscles. Emphasis on power at

the middle or end of the drive would emphasize more isolated and smaller muscles. Early application of power also means that the force being applied with the oar is not at its most productive angle given the distribution of force along the two vectors of the horizontal plane.

Some research (Soper and Hume, 2004) has shown that in pairs rowing, angular mechanics favors a slight timing difference. This balances the leverage of the bow and stern rower at different phases of the stroke relative to the center of mass of the shell. In larger boat classes, this biomechanical principle has led some coaches to select a balanced distribution of port and starboard rowers rather than the more traditional unbalanced alternating of port and starboard rowers.

Ergometer-based biomechanical research shows that the maximum force applied by rowers occurs during the initial strokes of a race as the shell is being propelled from a dead stop (Hartmann et al, 1993). Hartmann's research shows that the force applied throughout the body of the race is not more than 70% of the maximal force at the start. Peak force during a stroke tends to decrease throughout a race until the end of race sprint at which time increased power can be expended. The major change in power is due to boat acceleration at the start. However, rowing at 70% of maximum power suggests the possibility that some degree of extra power could be available for Big-10 drives during the body of a race when a crew is consciously trying to make a move on other crews.

The characteristics of a typical rowing stroke are well diagnosed. However, there is little agreement on a common rowing style and race strategy. Soper and Hume (2004) recently surveyed the contributions from biomechanics in the literature. Their bibliography contained 110 references, yet they concluded that there is very limited research on the ideal rowing

technique. Collegiate rowing styles and strategy have traditionally been taught based on school tradition, subjective coaching beliefs, and interpreting the results of previous races. This subjectivity remains largely unchanged due to a lack of rowing performance predictors in the literature.

Part of the difficulty in reaching consensus on rowing technique and strategy are the conflicting conclusions reached from diverse studies analyzing different aspects of the rowing stroke. For example, a comparison of propulsive versus transverse forces on the oar suggests that force application is most inefficient at the catch and finish (Sanderson and Martindale, 1986). However, a study of hydrodynamic drag and the associated benefits of maintaining a steady boat speed suggest that rapid force development at the catch and longer stroke maintenance at the finish should be emphasized instead of applying the highest peak force in the middle of the drive (Kleshnev, 1999).

Even if you assume that exploding at the catch with power is a more effective technique for short rowing pieces, producing very steep force-time curves may be very costly in terms of lactic acid accumulation and energy production (Seiler, 1997). Therefore, sustaining this technique over the duration of a 2000-meter piece may not be a sound strategy if one wishes to conserve and pace the usage of the rower's limited aerobic physiological resources. However, this is not scientifically proven either way.

The shape of the force power curve over the duration of a stroke has been widely studied. Jones and Miller (2002) found that rowers display individual or signature stroke profiles in terms of the shape of their force power curve over the duration of their stroke. Such individual stroke

profiles are used to provide a basis for distinguishing the features of the stroke and classifying individuals.

The Australian Institute of Sports compiled a database of over 400 biomechanical sessions including 6000 rower-samples over a 4-year period. Using this data, Kleshnev (2001(2)) found that rowers could be classified into two types – those who have a classic rowing style of working their legs and trunk sequentially vs. those who apply leg and trunk strength more simultaneously. Most use the classical style, but 15-20% of rowers use the simultaneous style. This research offers the prospect to someday arrive at a more commonly agreed upon ideal style of rowing based on a scientific foundation. We are not there yet, so the rowing style debate continues.

Biomechanical Simulation Models

Biomechanical research has been done to quantify and simulate the vector and angular mechanics of the oar, rigging, and shell. Research has been done to measure and model the timing of force application, and to study the speed variations of the rowers, equipment, and shell over the duration of the stroke. Force-segment biomechanical models have been developed to study the linear and angular forces among the various segments of the body in relation to the forces that are ultimately applied to the oar handle, foot stretcher, and seat.

In one comprehensive paper reviewing the mechanics and biomechanics of rowing (Zatsiorsky and Yakunin, 1991), force-segment components (see Table 2-4) were described and mathematically modeled in terms of formulas.

Table 2-4: Force-Segment Component Model (Zatsiorsky and Yakunin, 1991)

<ol style="list-style-type: none"> 1. Oar movement <ol style="list-style-type: none"> a. Kinematics <ol style="list-style-type: none"> i. Angular kinematics (angles characterizing oar position) ii. Oar blade trajectory b. Dynamics <ol style="list-style-type: none"> i. Forces acting on the oar ii. Work and power of forces c. Effectiveness of oar propulsion
<ol style="list-style-type: none"> 2. Boat movement <ol style="list-style-type: none"> a. Kinematics <ol style="list-style-type: none"> i. Velocity and acceleration b. Dynamics <ol style="list-style-type: none"> i. Forces applied to the boat ii. Work and power of forces
<ol style="list-style-type: none"> 3. Rower movements <ol style="list-style-type: none"> a. Forces applied to the rower's body b. Work and power of forces
<ol style="list-style-type: none"> 4. Motion of RBSO (rower-boat-sliding seat-oars) system <ol style="list-style-type: none"> a. Models and equations b. Transfer of momentum c. Propulsive forces

More recently, William Atkinson has developed a FORTRAN model to analytically compute the dynamics of rowing (Atkinson, 2001). He has used his ROWING model extensively to self-publish “what-if” analytical findings and interpretations on the Internet. At the heart of his model are a rowing biomechanics force-segment model and a stroke geometry model. Atkinson explains that his model “contains the detail necessary to give it predictive power in the study of crew-to-shell momentum exchange options, and as a reliable substitute for the expense, difficulty, and irreproducibility of field trials in the evaluation of experimental rowing styles, oar blades, and of boat designs and arrangements.”

To summarize the effects of biomechanics on racing strategy, it is generally regarded that more experienced crews will row more skillfully and therefore more efficiently and effectively.

It is also generally understood that having the best equipment and having it skillfully rigged provides a competitive advantage. The advantages of experience, skill and equipment can often offset the size advantages of larger crews. A crew's beliefs about rowing style and the relative skill of the competitors can affect race strategy and the psychology of the race. The combination of human talent and equipment (or skill-based biomechanical advantages) defines the "base capability" for a crew. Nevertheless, how well this crew performs on race day is also a function of the six other factors in the model of crew race performance.

*Boats do NOT move forward because (necessarily a mass of) water is moved backward.
Boats move forward because the mass of the earth is moved backward.*

...

A blade of 100 percent efficiency disturbs no water whatever.

William Atkinson
(2002)

Race Scenario: Physiology (P)

The race scenario is an important factor in race strategy. A well conditioned crew should bring with it the training, conditioning, and physiological capability needed to compete well, given its race strategy for the given race scenario. However, excellent human talent, rowing technique and proper equipment are not enough. The crew must also be fit and well conditioned for the race distance it is rowing. The crew must balance and spend its energy reserves over the duration of the race. This involves pacing the stroke rate and level of energy expenditure to match the gearing of the crew's rigging so that the crew's energy "budget" is used optimally over the 2000 meters.

There is a large and growing body of research and data on rowing physiology and energy utilization. Rowing requires a combination of strength and endurance. Thus, from a physiological standpoint, the competitive goal is to find ways to deliver the most oxygen to muscles as fast as possible while balancing the pace of energy usage over the duration of the race. For short periods, muscles can work without oxygen through anaerobic respiration. For longer periods, oxygen is needed to sustain aerobic energy (along with the consumption of either glucose or fat).

The body's capacity to use oxygen is measured in terms of oxygen uptake, designated as VO_2 , which is expressed in terms of liters of gas absorbed per minute through breathing. There is a limit to the maximum oxygen uptake possible for an individual – the VO_{2max} . Training increases VO_{2max} and the level of exertion a person can sustain for long periods of time. Although many things determine VO_{2max} , the predominant factor is the heart's pumping capacity to move oxygen-rich blood throughout the body. Through training, the distribution

system improves as blood vessels get wider and the number of capillaries in muscle tissue increases.

About 85% of the energy requirement during a crew race is supplied aerobically (Seiler, 2005), while the remainder is supplied via anaerobic pathways. Other literature survey research (Maestu, 2004) has yielded varying estimates ranging from 67% to 86% aerobic, with the more recent research placing the aerobic component around 86%.

The anaerobic energy supply can be further divided into anaerobic lactic and anaerobic alactic components (Hartmann and Mader, 2005). Anaerobic energy usage produces lactic acid. Anaerobic lactic energy is not immediately available for the first two to four seconds of exercise. In the first few seconds, energy must predominantly come from anaerobic alactic processes that consume high-energy phosphates (ATP/CRPH).

During the acceleration phase at the start of a race, 40 to 45% of total energy is anaerobic (Hartmann and Mader, 2005). Next, in the transition phase, 20 to 30% of total energy is anaerobic. During the body of the race, only 5 to 10% of energy is anaerobic. In the final sprint, anaerobic energy increases to 10 to 15% of total energy. Over the total duration of the 2000-meter race, anaerobic energy produces 15 to 20% of the total energy. For a well trained rower, the anaerobic lactic supply produces about 15% of the total energy, with about 5% coming from the anaerobic alactic supply (the primary energy source is the first few strokes of the race).

The exact estimate of the aerobic/anaerobic mix may not be as important as how to apply this knowledge in developing race strategy. For purposes of strategy formulation, it is sufficient for a coach to just be able to effectively estimate the pacing and effects of aerobic and anaerobic burnout – without even understanding the underlying physiological processes. Consequently, all

coaches seek to understand the capacity of their crews to race at higher stroke rates (burning anaerobic energy) during the racing start and during the race-ending sprint.

Where coaches disagree widely is the steady-state stroke rate and energy usage levels to adopt during the middle of a race. They also disagree on the desirability and frequency of use of Big-10's during the body of the race in order to make planned "moves" on other crews at key psychological points during the race. Although such moves may provide psychological advantages to crews as they strive to implement their race plans, these extra energy expenditures may just be borrowing from energy reserves otherwise rationed for use later in the race.

The concept of a maximal lactate steady state (MLSS) has been studied (Billat et al, 2003) as a bridge between biochemistry, physiology and sport science. MLSS is the highest point in the lactate turnover equilibrium – the point at which lactate appearance and disappearance are balanced. MLSS provides a basis for understanding the energy pacing possible in a 6 minute crew race, as well as the means and consequences of varying the pacing of energy usage throughout a race.

MLSS is the highest blood lactate concentration (MLSSc) and associated work load (MLSSw) that can be maintained over time without increasing the blood lactate level. Time to exhaustion is improved by training. For trained athletes, Billat estimates endurance time at MLSS to last about an hour. The average velocity for a marathon runner is just below the MLSS workload (MLSSw). Crew races which average around 6 minutes are much shorter in duration than a 2-hour plus marathon. Therefore, the average energy pacing of a crew race is above the steady-state MLSSw workload, and lactate levels should peak at the maximum possible level at

the end of the race. Consequently, crew races are often referred to as 2000-meter “sprints” even though the high consumption of aerobic energy reveal crew races to also be an endurance sport.

The physiological science and the strategy behind a 2000-meter crew race is not simply about maintaining a steady-state effort, but rather about how much above the steady-state MLSS a crew should expend its energy, the timing of when to exceed this threshold, and whether deviating the pacing above the level of MLSS is somehow strategically or tactically warranted. The extra energy expended to support a Big-10 or other tactical drives accelerates the timing of energy usage, but is not the sole rationale for a crew to row above the MLSS equilibrium. Somehow, the crew needs to burn its energy above this equilibrium so that all of its anaerobic energy is consumed.

The physiological means of obtaining the extra energy for a Big-10 or similar drive may be enhanced by the “fight-or-flight” enzyme – glycogen phosphorylase. Glycogen reserves are a factor in exhaustion at MLSS (Billat et al, 2003), and glycolysis can be mediated by adrenergic activity. Therefore, it is possible that the motivational psychology of calling a Big-10 could lead to a fight-or-flight mental state triggering enzymes or adrenaline that would lead to a temporary burst in energy and resultant boat speed. This would explain why Big-10 style moves could provide a temporary burst in speed when the rowers are already thinking they are rowing at full power and are already burning their energy at a rate above the relative comfort level of the MLSS steady state.

The tolerable duration limit of high intensity exercise can be modeled as a hyperbolic function of power (or for rowing, velocity) with an asymptote termed critical power (or critical velocity). An example of a two-parameter hyperbolic model (Hill et al, 2003) is:

Time to fatigue = $AWC / (\text{velocity} - \text{critical velocity})$

Where:

AWC = an indicator of total anaerobic capacity

Critical velocity = a measure of sustainable anaerobic capacity

A variety of two and three parameter hyperbolic models have been formulated and studied for rowing or extended to rowing from other sports (Hill et al, 2003). These models may include such physiological indexes as maximal sustainable aerobic power, anaerobic work capacity, and the maximal velocity possible based on a combination of neuromuscular and skill factors. These models suggest that world class rowers can sustain between 66 to 77% of their maximal rowing power (needed at the start of the race) over the duration of a 6-minute 2000-meter race. This work rate intensity level for these models is appreciably above the lactate threshold (Fukuba et al, 2003).

The consequence of exercising above the steady-state critical power and beyond the endurance limit for this level of power is exhaustion. Continued exercise after exhaustion is only possible by reducing work rate and the corresponding power output to a level below the critical power (Coats et al, 2003). This work rate after exhaustion is reduced to a level that relies predominantly on aerobic energy transfer, and in so doing, allows exercise to be sustained.

In terms of racing strategy, a crew can race significantly above its level of critical power for only a limited duration. After achieving exhaustion, the crew is burnt out and will continue to row only at a sub-optimal level of power. Therefore, one of the keys to race strategy is to time the level of intensity and duration of power to achieve exhaustion near the end of the race.

Otherwise, the loss of power and speed after exhaustion may offset the gain from rowing earlier in the race at a work rate above the critical power.

The amount of energy available above the level of critical power can be thought of as a constant and finite level of energy store (Fukuba et al, 2003). This is comprised of a phosphagen pool, an anaerobic glycolytic component, and an oxygen store. This pool of energy is modeled as a hyperbolic curve that is a function of power versus duration, and is considered to be the equivalent of the oxygen deficit or the subject's anaerobic work capacity. This work capacity in excess of critical power can be utilized rapidly by exercising at a higher work rate, or may be sustained for longer durations by exercising at lower work rates.

Research (Fukuba et al, 2003) also suggests that this excess work capacity is a fixed amount and not affected by the pattern of power variations – at least for power ranges in cycle ergometry from 100 to 134% of critical power. From the standpoint of race strategy, this supports the notion that crews could strategically vary their level of energy consumption during a race, and in a wide range of patterns, up until the point where their anaerobic energy store is cumulatively consumed and exhaustion sets in.

There is a strong relationship (Roth, 1991) between physiology (energy components, structure of muscle fibers, training condition), biomechanics (rowing technique, structure of movement), and training methods (means of training, duration, intensity and frequency). Consequently, Roth advocates “unified training methods” that reflect these relationships.

Using indoor rowing tanks and force/time impulse measuring devices, he compared the force/time power curves and physiological responses to different styles of rowing emphasizing power at the three different phases of the drive:

1. BD: beginning of the drive (legs and upper body muscles)
2. MD: middle of the drive (legs, upper body and arms muscles)
3. ED: end of the drive (arms and upper body muscles)

His research showed that there is a connection between the form of rowing technique (stroke pattern, force/time-curve) and the fitness required. When emphasizing the beginning of the drive, there is a more intensive aerobic demand on the rower. The BD emphasis is biologically realized primarily through fast twitch muscle fibers rather than slow twitch fibers essential for endurance.

Roth interprets this data as supporting a rowing technique with emphasis toward pressure at the beginning of the drive, but also interprets the applicability of this style more toward short distance racing. He cites research on the negative effects of lactic acid accumulation and cites examples of well conditioned world class rowers whose performance decreased in the last third of the race. However, his findings also support the tactic of using BD emphasis as a technique for achieving extra speed in racing starts, sprints, and Big-10's.

*Endurance is one of the most difficult disciplines,
but it is to the one who endures that the final victory comes.*

Buddha
(6th Century, B.C.)

Race Scenario: Weather and Environment (W)

Weather and environmental conditions are important aspects of the race day scenario. Unpredictable factors such as wave height can affect the ability of a crew to row well (including minimal splashing and a clean catch and finish). Headwinds and tailwinds or currents in the water also determine the effective distance of the race in terms of expected time and total strokes. A head wind slows the race. A tailwind speeds up the race. Other environmental influences affecting crew comfort level and expected race speed include temperature (air and water), water depth, water density, altitude, and air pollution.

For example, William Atkinson (2007(1)) used his ROWING biomechanics model to study the effects of water temperature and corresponding water density. A difference in water temperature of 10 degrees (C) on an eight oared crew will change the expected time over a 2000-meter race by about 4 seconds or 1.3 lengths.

Not all conditions affect each crew fairly. Some lanes may have advantages. Random events can occur including obstacles in the water or wakes from other boats on a lake or river. Even though courses are laid out to offset the curvature advantages of inside lanes, it is inevitable that turns in the course can affect perceived race positioning and therefore race psychology.

In recent years, all world rowing championships are raced on straight and narrow channels usually custom built for crew racing. Water current, water depth, and the random effects of other environmental factors are minimized. However, until the day that the first crew race is held on an indoor course, the effects of wind direction and speed are still uncontrollable factors that can shorten or lengthen race duration, and can have unfair effects on racing lanes.

The referee handbook specifying the Rules of Rowing (US Rowing Referee Committee, 2008) specifies the following factors that must be considered before a race course is judged suitable for a registered regatta:

1. Whether the course is uniformly sheltered from the wind.
2. Whether the course is free of obstacles lining the shore, such as trees, buildings or dikes, which would cause unequal wind or water conditions on the course.
3. Whether the course is free of any current, or whether any current that does exist is slight and equal across the course.
4. Whether the banks of the course will absorb rather than reflect waves.
5. Whether the course is free of obstructions such as bridge abutments or islands.
6. The prevailing climate.

The Rules of Rowing also designate courses as class A, B or C in order to specify the suitability of a course for championship regattas. Class A courses must meet the following environmental standards:

1. There must be no bends or turns.
2. Any current in the water shall be less than 1 meter per minute.
3. There must be a water depth that of at least 3 meters throughout the course.
4. There must a perimeter of at least 5 meters separating the course from the shore or any fixed obstacle, and there may be no fixed obstacles on the course.

Class B and C courses relax these standards. For example, a Class B course restricts any current in the water to less than 6 meters per minute; the water must be deep enough only to ensure safe racing; and fixed obstacles are allowed on the course as long as they are clearly marked and do not obstruct the proper path of a crew.

Class A international race course standards are very similar. Nevertheless, the effects of wind cannot be controlled and can have a dramatic effect on race times. Evidence of the environmental effects on race times can be observed in the average boat speeds and winning times of world championship crews from year to year.

Statistical regressions on winning times over 14 years (Kleshnev, 2006) reveals a gradual pattern of improving times in 13 out of 14 boat classes (women's double sculls being the exception). Nevertheless, fluctuations in winning times are substantial and important in terms of race strategy. Winning times for both men's and women's 8's competition can vary by 40 seconds or more from year to year. This is certainly due to environmental conditions – not due to the quality of crews varying by this much.

Wind and weather can vary dramatically within a short period of time – sometimes just a matter of minutes. This is a critical aspect of the race scenario for which crews need to be prepared. Part of the challenge of each coach is to anticipate the rowing conditions their crews will actually face at race time. The gearing of the rigging and oars can be adjusted to affect the leverage and level of energy needed per stroke for a given stroke rate. A crew can be prepared (gearing, stroke rate plan, and expected pace of energy expenditure) for a race expected to last 6 minutes and yet experience race conditions that can be as much as 40 seconds faster or slower.

Rowing is an outdoor sport.

Larry Gluckman
(Anderson, 2001, p.221)

Performance Execution: Quality of Execution (Q)

One can define “performance” simply in terms of how well a crew placed in the race. Thus, winning is the best performance possible, and losing means their performance was the worst possible. Consider this to be the performance result.

For purposes of a crew race performance model, "performance execution" is defined based on the combination of the quality of execution (Q) of a crew and the effects of race psychology (R). A losing crew could still have rowed very well, and perhaps even better than was expected from them. A winning crew could have performed poorly in terms of their effort and execution, but still easily win a race due to the weakness of their competition. A crew's quality of execution is determined not simply by winning or losing, but whether the crew executed according to its potential.

The quality of execution of a race can be judged in three ways:

- **Strategic Execution** – whether the crew adhered to its race plan, and whether the race plan was the best choice for the race scenario.
- **Technical Execution** – whether the crew rowed mistake-free in terms of blade work, steering, and other imperfections or misfortunes.
- **Teamwork and Synchronization** – whether the crew rowed in a coordinated manner, the rowers' styles blending well together, and possibly even achieving a “swing” effect.

Strategic Execution

A race plan is the combination of strategy and tactics planned for a race. The plan is established by the coach but needs to be implemented by the crew. The coxswain may need to react to unexpected race circumstances, and make appropriate tactical adjustments based on the contingencies for which the coxswain has been trained. If a crew executes the coach's strategy as planned and if the crew responds appropriately in terms of tactical contingencies, it has performed well in terms of strategic execution.

Although a crew can follow its race strategy and tactics perfectly – making all the moves and stroke rate changes exactly as planned – the crew may still fail to perform as well as expected relative to the competition. This does not necessarily mean that the crew failed in terms of strategic execution. Poor strategic execution is when a crew unintentionally deviates from its strategy and tactics. A failure to execute race tactics properly could include settling too high or too low off of the racing start. It could also include timing errors on the part of the coxswain, such as accidentally changing stroke rates at the wrong time during a race. The consequence of the coxswain calling a sprint much sooner than planned could be that the crew becomes totally exhausted before the race ends -- thus resulting in suboptimal physiological performance.

Coaches sometimes allow a coxswain tactical discretion as to whether to call up the stroke rate at the end of a race earlier or later than planned. The coxswain may also choose to not call up the stroke rate at all if the crew seems safely in the lead. If these contingent tactical choices fail to achieve the desired effect, this can also be viewed as a failure in race strategy execution.

Sometimes, the coach has chosen the wrong race plan for the crew given the race scenario that day. A strong head wind could make the race last much longer than originally planned. A tail wind can have the opposite effect. The coach has geared the rigging of the crew and chosen a race plan based on a set of assumptions about the race conditions. Should the actual race conditions be different than planned, the crew or coxswain might or might not choose to deviate from their race plan. Regardless of the cause, executing the wrong strategy and tactics for the specific race day scenario can be viewed as a failure in strategic execution.

Technical Execution

Many things can go wrong that are the result of technical errors on the part of the rowers or the coxswain. At elite levels of international competition, no major errors are expected, yet even minor errors could still produce the difference between winning and losing in a very close race.

Technical errors in rowing style can be subtle and difficult to perceive by race observers, but still affect the feel of the boat. This includes sloppy blade work, imperfect timing and synchronization, and a boat that is not well balanced (occasional tilting toward the port or starboard side).

Major technical errors can have more dramatic consequences for a crew, but seldom occur in elite competition. These can include catching a full or partial "crab" (when the rower's oar gets stuck in the water at the finish of a stroke), collisions with course obstacles, interference with another crew, jumping the start, broken equipment, and injuries to rowers. Misfortunes can

dramatically affect crew performance and race times. Some rules infractions can even result in the crew being disqualified from the race.

Table 2-5 lists many of the racing events that can occur in a crew race. These events are from cards used in a board game designed to reenact crew races (Cornett, 1974). Some of these events simulate the effects of exceptionally good performance. Other events reflect errors in strategic or technical execution. Still other events are the result of the racing environment or reflect the psychological morale effects of specific race circumstances.

Bill Stowe (Stowe, 2005) describes an example of a random event that had disastrous consequences in the 1964 European Championships. The Russian crew was in the last 500-meters of a very close race with the West Germans when they ran into a duck peacefully swimming on the course minding its own business. “The duck made a big fracas with its wings and managed to tip a national eight off balance.” The Russians then gave up a quarter length lead and ended up losing by 2/100ths of a second. Stowe believes the duck could have made the difference.

Table 2-5: Event Cards from Collegiate Crew Boardgame

Event Trigger	Decision Choice	Due to Morale	Influence on Stroke Rate	Race Planning	Cause Category	Card Title	Card Value
Automatic	Optional				Racing Environment	Unfair wind conditions	3
Automatic	Optional				Racing Environment	Unfair current in water	3
Conditional	Optional		Stroke Rate		Racing Environment	Strong head wind	0
Conditional					Random Event	Other crews settles too high from racing start	0
Conditional					Random Event	Crew on starboard can't hear their cox	0
Conditional			Stroke Rate		Random Event	Crews hit by wake from some joker in power boat	4
Conditional					Random Event	Broken oar	0
Conditional					Random Event	Other crews sinks in rough water	0
Conditional					Random Event	Neighboring crew steers out of its lane	0
Timing	Timing & Who				Random Event	Fat coxswain	0
Judgement	Optional				Random Event	False start	1
Automatic					Crew performance	Fast start	2
Automatic					Crew performance	Good settle from racing start	3
Conditional			Stroke Rate		Crew performance	Finishing kick	1
Conditional					Crew performance	Cox steers straight	2
Conditional			Stroke Rate		Crew performance	Good recovery from crab	4
Judgement	Optional				Crew performance	Crew uses fancy foreign-made racing shell	0
Judgement	Optional			Tactic	Crew performance	Jump the start	1
Timing	Timing		Stroke Rate	Tactic	Crew performance	Concentration breakdown	3
Timing	Timing			Tactic	Crew performance	Sloppy sprint	1
Timing	Timing	Morale		Tactic	Crew performance	Big sprint	3
Timing	Timing	Morale		Tactic	Morale tactic	Bowman lets out war hoop	0
Reaction		Morale		Tactic	Morale tactic	Big 10 to move	2
Reaction		Morale		Tactic	Morale tactic	Big 10 to hold	1
Reaction		Morale		Tactic	Morale tactic	Counter Big 10	1
Automatic		Morale		Tactic	Morale tactic	Big 10 for 3-man's sister on shore	2
Timing	Timing	Morale		Tactic	Morale tactic	Big 10 for power	2
Timing	Timing	Morale			Morale characteristic	Crowd psyches crew	2
Reaction		Morale	Stroke Rate		Morale characteristic	Good pressure crew	3
Reaction		Morale	Stroke Rate	Strategy	Morale characteristic	Crew rows a holding race	3
Reaction		Morale	Stroke Rate	Strategy	Morale characteristic	Come from behind crew	4
Automatic		Morale		Strategy	Morale characteristic	Crew rows like 1970 Washington crew	4
Reaction		Morale	Stroke Rate	Strategy	Morale characteristic	Crew rows like 1971 Cornell crew	4
Timing	Timing Optional	Morale	Stroke Rate	Strategy	Morale characteristic	Crew rows like 1972 Pennsylvania crew	4
Timing	Timing	Morale		Strategy	Morale characteristic	Crew rows like 1973 Wisconsin crew	4
Conditional			Stroke Rate	Strategy	Stroke rate planning	Low stroking crew	2
Conditional			Stroke Rate	Strategy	Stroke rate planning	High stroking crew	1
Timing	Timing Optional		Stroke Rate	Tactic	Stroke rate planning	Call it up or stretch it out	n/a

Teamwork and Synchronization

Synchronization of the various elements of the rowing stroke and the timing of force application has been studied among rowers to explore the potential advantages and even the disadvantages of each rower being perfectly in synch with each other. Most coaches agree that good synchronization is highly desirable.

However, the non-linear effects of hydrodynamic water resistance suggest that a perfectly asynchronous rowing style would be superior due to the benefits of maintaining an even boat speed. In 1931, the London Rowing Club actually experimented with “syncopated” rowing where there is always at least one pair of oars in the water at one time. A video showing this technique can be found on the Internet (ITN Source, 1931). Another web site (Goodfellow, 1997) provides a graphical comparison demonstrating the theoretical advantages of a sequential asynchronous stroke. Stephen Goodfellow suggests that the benefits in momentum and torque are analogous to why car engines have cylinders that fire at different times.

William Atkinson used his ROWING biomechanics model to analyze the effects of asynchronous rowing. His model has previously shown that external momentum work can be as high as ten percent of the total work output and appears at the footboard (Atkinson, 2007(2)). By making the stroke period of each rower out of phase with each other, his model calculates that there would be a loss of speed of about 2 percent by rowing asynchronously (Atkinson, 2004). His interpretation is that confining the shell speed to its average value makes it impossible to transfer useful work to the boat through the footboard. Thus, the work that is lost at the footboard more than cancels the reduction in hull resistance due to maintaining constant speed.

Other research suggests that successful rowing performance is influenced by the consistency of intra-stroke fluctuations in boat velocity and that wider fluctuations are associated with less successful technique (Soper and Hume, 2004). Fluctuations in boat speed occur throughout each intra-stroke phase of the rowing cycle. As stroke rates increase, intra-stroke fluctuations in boat velocity significantly increase. The fluctuations tend to be asymmetrical around the average boat speed with greater reductions in boat velocity than the increases. The non-linear relationship between hydrodynamic drag and boat speed causes stroke-rate fluctuations to be sub-optimal in terms of the energy expenditures needed.

Kleshnev (1999) studied blade efficiency and hydrodynamic drag effects as a function of stroke rate and the timing of power during a stroke. His on-the-water biomechanical measurements led to the conclusion that rapid force development at the catch and longer maintenance at the finish should be emphasized rather than peak power in the middle of the drive. He also found that increasing stroke rates led to an increase in velocity variation and therefore a measurable loss of efficiency.

One of the most widely cited studies on rowing coordination and consistency is by Wing and Woodburn (1995). They defined three important components to crew coordination: having a common periodicity (cycle of activity), good synchronization (correspondence of phase), and similar force-time profiles. Wing and Woodburn graphed force-time profiles for individual rowers over the length of time rowing at power. Their illustration is quite original in that it demonstrates how crew exhaustion affects the force-time curve. The Wing and Woodburn study examined the similarity of rowing styles among the crew and how consistently the rowers maintained these styles over time. They offered the interpretation that greater synchronization

results in less wasted effort, and that the wasted effort is due to the inefficiencies of turning moments associated with poorly synchronized strokes and the unequal forces produced by each rower.

The "Swing" Effect

What is the definition of “swing?” This effect is rarely achieved even amongst the best of crews. The concept of swing is somewhat controversial in that not all coaches and crews believe in this effect. Instead, they attribute such unexpected speed to simply exceptional effort (or psychological affect). Although nobody has yet provided a scientific explanation for swing, the rowing literature contains many references to swing as an unusual performance enhancing experience that is generally associated with good synchronization among the crew. See Table 2-6.

Hundreds of papers have been published on the kinematics, physiology, and psychology of rowing (see Soper and Hume, 2004). Much of this research was done with a purpose of finding out how to enhance performance and speed, yet Soper and Hume observe that “predictors” of rowing performance are lacking in the literature. Jones and Miller (2002) assert that the objective of the study of rowing biomechanics is to make boats go faster.

Nevertheless, the literature seems devoid of any direct attention to researching swing, how it happens, its magnitude, and strategies to take advantage of this effect. Some of the literature, such as Wing and Woodburn (1995), examines the synchronization of rowing styles and force curves. However, the typical investigation is to consider force patterns as a behavioral phenomenon rather than as a performance enhancing rowing style.

Table 2-6: References to the Rowing Term “Swing”

Source	Definition of “Swing”
US Rowing Nomenclature (US Rowing Nomenclature, 2008)	“Swing is a hard-to-define feeling when near-perfect synchronization of movement occurs in a shell, enhancing the performance and speed of the crew.”
Bair Island Aquatic Center terms (Bair Island Aquatic Center, 2008)	“Attaining aquatic Nirvana where everyone is in tight synchronization.”
"Power Rowing" by Gene Horton (Houston Rowing Club, 1990)	“There is also a spiritual plus "connecting" with fellow rowers. In a single shell there are moments when oarsman, boat and water, come together as a single force of nature, and the shell seems to move effortlessly across the surface. This gratifying sensation is magnified in a team boat, which is capable of producing what is known as "swing" - when the crew fuses into a rhythmic, single-purpose animal, and the shell beneath them suddenly stirs with life.”
“Feel No Pain" by John Seebrook (Seebrook, 2003)	“... the boat moved as if it had entered the quasi-mystical state of oneness that rowers call "swing" ”
Glossary from “The Down and Dirty Guide to Coxing” by George Kirschbaum (Kirschbaum, 2003)	“A feeling in the boat, when the rowers are driving and finishing their strokes strongly, while getting good layback. The boat feels like it is accelerating and flowing well on the recovery.”
The Coxswain’s Manual by Joe Keeley (Keeley, 1998)	“The sensation of everyone rowing in synchronization with everyone else so that less effort is needed to propel the boat forward.”
Relaxing and Focusing on Race Day. (Joy, 2005)	“Flow is the effortless swing, or stride, or stroke, and in rowing flow produces effective shell run. Flow involves being totally integrated, mind, body, and environment.”

Although there does not appear to be any direct research on swing as a performance-enhancing phenomenon, some of the research hints at what might contribute to this effect. Jones and Miller (2002) examined the period around the catch and the effects of momentum and changes in momentum on boat velocity. Among their conclusions,

“The slowing of the boat is exaggerated when members of the crew do not manage to place the blade into the water for the catch at the same time as the rest of the crew, or when crew

members begin to push off for the drive before the blade has entered the water. This is a critical action which results in a major deceleration of the boat.”

Based on this insight, consider the potential benefit to a crew that has near perfect synchronization at the catch including a synchronized style of not hanging at the catch, simultaneously hitting the catch before pushing off on the drive, and then uniformly applying early power on the drive. Theoretically, this would minimize the loss of speed due to momentum changes, reduce hydrodynamic drag, and allow for increased power to be applied early in the drive.

Research by Dawson et al (1998) underscores the difficulty in achieving good timing. They examined sources of variance among rowers and concluded that the major source of variance was the recovery phase, and that the most difficult part was the timing of the return to the catch position.

Further research on style aspects of the catch is by Soper and Hume (2004). They summarized research on international scullers that showed that limiting the reduction of boat velocity during the catch and initial drive phase was strongly correlated with performance. This supports a quick catch as an effective style of rowing. However, the timing effects of synchronized styles were not considered. They diagrammed a deterministic model of mechanical factors that influence performance. Although the term “time” is used nine times in this model, the concept of synchronized timing is not included.

Contrary to popular theory that synchronization is highly desirable, some research suggests that asynchronous rowing can have benefits. Baudouin and Hawkins (2004) studied

pairs rowing and found that the timing of peak force varied between Bow and Stroke. This adjusts for differences in moment arms at different times during the stroke.

An earlier study by Baudouin and Hawkins (2002) examined drag forces and the effects of velocity changes. A significant finding from their research is that drag forces depend on the square of the relative velocity of the shell with respect to the water. This further underscores the importance of a quick catch with minimal hang time in order to help maintain boat speed.

Perhaps, the most thorough research on the dynamics of coordination within crews is by Hill (2002). He studied individual force curves in terms of synchronization of the onset and finish of a stroke, individual area differences from stroke to stroke, total difference relative to the crew average, and form differences in the shapes of curves. He found that individual rowers have their own individual force patterns, but that adaptation in styles occurs over time when rowers are combined in crews, especially when they have been rowing together for a long time. Hill did not study, but asserted that rowing is more efficient when crew coordination is high because of reduced yawing, rolling, and pitching – effects that waste effort due to increased friction.

A well-synchronized recovery and catch is highly valued. Some rowers who have personally experienced what they consider to be the swing effect attribute this phenomenon to a feeling in the boat that has more to do with the recovery and catch, rather than the timing and power exerted during the drive. According to Jones & Miller (2002), “The slowing of the boat is exaggerated when members of the crew do not manage to place the blade into the water for the catch at the same time as the rest of the crew, or when crew members begin to push off for the drive before the blade has entered the water. This is a critical action which results in a major

deceleration of the boat.” Thus, it could be that the swing effect has more to do with an efficiently timed stroke that minimizes the negative effect of the momentum shift of the rowers' weight, than it does with just rowing harder. If so, the swing effect provides an added speed benefit to the crew without affecting the physiological level of energy expended.

One unpublished research paper attempted to quantify the swing effect (Cornett, 2005). These findings were presented to a standing room only audience at the 2006 US Rowing Conference. The study examined the possible presence and magnitude of a swing effect by the Cornell varsity in the finals of the 1971 Intercollegiate Rowing Association (IRA) regatta. The swing effect was experienced in the Finals race, but did not occur in the Repechage race a day earlier by this same crew. Several techniques were used to verify and assess this effect including an analysis of a VRML 3D reenactment of these races, a reconciliation of 500-meter time splits between these two races, an analysis of the observed double spacing seen in the Finals race, and a survey of the participants from this crew for their personal impressions. The Finals race is estimated to have included a swing effect lasting from the settle of the start to about the 1000-meter mark. The magnitude of this effect was about 0.25 meters per second gain or about one quarter length per 100 meters. In all, the Finals crew is estimated to have gained about 1.5 lengths in speed over the Repechage crew from this effect alone.

The 1971 Cornell crew was an inexperienced collegiate crew. The varsity crew lineup had been juggled by the coach all season. The championship crew had only rowed together for about four weeks before competing at the nationals. Their stroke man had been pulled out of the third boat four to stroke the varsity, and had only raced a couple of races in his lifetime before

competing at the IRA. It could be that the Cornell crew's swing effect was something that inexperienced crews experience when they unexpectedly row really well together.

For purposes of elite crews competing at the world championship level, it remains a matter of speculation as to how often elite crews ever experience a dramatic swing effect, or whether they routinely experience it and just don't notice it as anything unusual. However, there are personal accounts of unusually good performances. For example, Lesley Thompson-Willie (Thompson-Willie, 2005) described her experience as a Canadian national team coxswain winning a gold medal at the 1992 Olympics. She describes rhythm and ratio (time on the slide compared to time with the blade in the water), the feel of the shell, and how the “boat will have a certain glide beneath you that is hard to describe.” She says there are only a few times that she has ever felt this in a race, but that the 1992 Olympic final was one race where “everything felt perfect.”

No member of a crew is praised for the rugged individuality of his rowing.

Ralph Waldo Emerson

Performance Execution: Race Psychology (R)

Simply rowing a good, technical race does not mean the crew performed to its potential. The quality of a crew's performance relative to its potential can be evaluated in terms of their psychological commitment to the race and their ability to focus on producing their best effort. The crew's effort and commitment to the race is a function of the psychology of their competitive positioning as the race progresses. The ability of a crew to make their best effort is also a function of how well the athletes focus on what they need to be doing and not be distracted by counterproductive thoughts.

Motivation and Effort

The effort a crew puts into a race is a function of how close the race is and whether the rowers are motivated to make the effort they are capable of exerting. Sometimes, holding back in a race is appropriate – such as when a crew is conserving energy for a future race. Sometimes, when winning a race, a crew may delay or withhold its sprint because it is unnecessary and increases the risk of technical errors or exhaustion. Influences on motivation and effort include race importance, perceived conditions in a race, the morale and character of the crew, and race psychology.

The psychology of leading or trailing your opponents in a race could affect the level of sacrifice rowers will make in how hard they pull. Crews are trained to row at “full power” throughout a 2000-meter sprint, yet physiological demands on the level of energy expenditure over 2000-meters can result in adopting a race strategy where crews pace themselves – either in terms of stroke rate or in terms of the effort expended per stroke. A full 100% effort may only

happen when rower commitment is driven by maximum motivational “affect”. When a coxswain calls a “big 10” in a race, the crew expects to move faster and gain against other crews. Theoretically, increased speed would not be possible if the crew was already at full power. Therefore, superior speed could be attributed to “affect” or a combination of morale, character, commitment, and belief in the crew’s prospects for winning.

Rowers are reacting at a primitive level to each stroke, subconsciously trading off their level of fatigue and the effort required with their level of motivation. Winning is often determined by psychological “affect” – the character of the crew, how much they believe in themselves, and their individual perception of their prospects for winning. In a close race, rowers may need to somehow find the extra motivation to make the extra effort needed to win.

If race psychology does not influence the dynamic performance of a crew, then every race might as well just be a time trial with crews rowing in isolation! Each crew would just execute its ideal race plan for today’s race scenario. Theoretically, a crew should know the ideal race plan to minimize its time over a 2000-meter race distance. Psychology is believed to contribute to both the level of effort and quality of effort needed to achieve a superior performance.

Klavora (1980) discusses the psychological basis of racing and compares the advantages and disadvantages of the “even-paced” racing strategy to the “early-lead” racing strategy. Rowing is the only sport where the athletes do not face the forward direction (except for the coxswain). The lead crew is in an authoritative position since the rowers can observe their trailing opponents and can react to their tactical intentions. They can counteract an opponent’s attack so as to hold onto the lead. According to Klavora, “In these instances “extra” energies

which, in normal circumstances, are not available to competing athletes, are mobilized in the oarsmen of the leading crew.”

Compare this to the even-paced strategy where a crew must row from behind in the race. Even pacing is the most economical way to row a race from a physiological standpoint. However, according to Klavora, it generates substantial psychological disadvantages. Not being able to see what is going on in the race, the rowers cannot directly judge who is leading the race, the distance they are lagging, and whether they are still within striking distance. Although the coxswain’s job is to inform the crew, “hearing does not mean believing.” Rowers are tempted to look around and peek over their shoulders – which can lead to disturbing the crew’s rhythm and balance.

According to Klavora, there are few rowers with a “strong enough personality to take the beating of rowing in the tail in the early phases of a race.” However, by rowing more economically, they may be able to overtake their opponents in the second half of the race. Overtaking opponents one by one can be “psychologically devastating for the tiring opposition, who are desperately trying to hold onto their lead.”

Johnson (1989) wrote about the psychology of pushing through the pain: “When the legs are screaming at the rower to stop ... how does he keep going?” She defines the purpose of sports psychology as to “help the athlete push beyond the limitations imposed by the rational mind.” She cites the example of Kris Karlson, 1988 world women’s lightweight sculling champion, who said that when she reaches the point where she feels she cannot go on, she often notices that she is moving on other people. “Wow! They are dying more than I am.” She starts “getting psyched” and manages to block out how dead she is and starts to focus on how she is

winning. Johnson's experience illustrates how crew races can truly be psychological competitions.

Concentration and Focus

Baltzell and Sedgwick (2000) interviewed elite level rowers and their strategies toward optimizing performance through their ability to cope with competitive pressure before and during the competition. They developed a "coping-excellence model of elite rowing" that blends intrinsic and extrinsic motivation along with habits of excellence. Extrinsic motivation is the desire to achieve external success – such as earning a place on a team, winning races or medals, and receiving the coach's praise. Intrinsic motivation is the innate desire to perform well and be in control while working toward their goal – such as to improve fitness, rowing technique, and rhythm. The habit of excellence reflects the principle that rowers race the way that they practice. Table 2-7 summarizes the coping scenarios most commonly suggested by those elite rowers who were interviewed.

This research emphasized the importance of having a race plan and focusing the rowers' mindset on what they can control including rowing efficiently, keeping relaxed and rowing with good rhythm. Pulling hard is necessary but most effective when it was a previously habituated response. Before the race, attention should be on the race plan which can be supplemented using mental skills such as imagery and goal setting. Baltzell and Sedgwick concluded that rowers need to be highly motivated to optimize their speed and performance, need to build habits of excellence into their daily practice, and that personal enjoyment and intrinsic motivation are more effective when coping with high levels of competitive pressure.

Table 2-7: Recommendations for Coping with Competitive Pressure (Baltzell and Sedgwick, 2000)

Most effective coping scenarios	Least effective coping scenarios
<p>Before the race:</p> <ul style="list-style-type: none"> • Adopt a “just do it” mindset. • Interpret pressure as a positive challenge. • Rehearse, think through, and discuss the race plan. 	<p>Before the race:</p> <ul style="list-style-type: none"> • High expectations and excessive focus on the outcome. • Ineffective preparation mentally, physically, and having no race plan. • Negative thoughts dreading the race and feeling out of control.
<p>During the race:</p> <ul style="list-style-type: none"> • Technical-physical efficiency including conserving energy, finding good rhythm, and focusing on technique. • Focus on the process of rowing rather than the race outcome. 	<p>During the race:</p> <ul style="list-style-type: none"> • Lack of control and feeling powerless over their ability to change how they are rowing and the speed generated. • Resignation and mentally giving up on winning the race.

Research in other sports examines other ways that athletes experience psychological stress. Bar-Eli et al (1992) investigated how high levels of arousal can lead to anxiety that negatively affects tennis player performance. They defined a “psychological performance crisis” as when an athlete has difficulties performing a task in competition due to extreme physical and psychological arousal. They were able to correlate impaired motor performance with high levels of stress. Although their research was directed toward tennis players, the principle could be extended to rowing in that a stressful race situation could lead to a loss of internal focus and diminished technical performance.

Tate et al (2006) studied techniques for modeling the relationship between athletic performance and levels of psychological affect (i.e. arousal). They proposed that there is an optimal range of affect within which an individual athlete’s performance is enhanced (graphed as an inverted U-diagram). They termed this the “Individual Zone of Optimal Functioning (IZOF)”

and likened it to how athletes will sometimes characterize themselves as being “in the zone” when competing. Being too high or too low on the affect scale can lead to suboptimal or even dysfunctional performance (i.e. the Individual Zone of Dysfunctional Performance or IZOD). The performance-affect relationship is believed to be unique for each individual, but to remain relatively stable over time for an individual.

The need to achieve a balance in the optimal amount of motivation and the need to focus on the most effective types of motivators has led many authors to research and propose how to train athletes psychologically. Waitley et al (1983) described how the Eastern Europeans were the first to employ sports psychologists on the staffs of their national teams. They state the goal of sports psychology is to “optimize competence through the development of psychological skills that will permit athletes to enhance performance and gain maximal satisfaction.”

Waitley et al (1983) also presented an inverted U-diagram similar to the model by Tate et al (2006). To address the need for balance, they recommended a variety of stress reduction techniques that could be taught to athletes by sports psychologists, including active rest, deep muscle relaxation, biofeedback, and assertiveness training. Assertiveness training means being “brain-controlled” rather than “emotion-controlled.” Consequently, they advocate training techniques in imagery training, cognitive reconstruction, and mental rehearsal.

According to Horsley (1989), asking rowers to “concentrate” is too vague. To improve their concentration, they must be given specific information and taught to work on specific skills – both mental and physical. The attentional demands of rowing are constrained by the brain’s limited capacity for processing short term memory, and by individual attentional style narrowly focusing on internal or external sources. Internal focus when racing includes awareness of

lactate build-up, muscle tension, breathing control, task-related thoughts, and awareness of rowing technique. External focus when racing includes awareness of the coxswain, his/her instructions, race officials, the boat and water, teammates, other crews, and other coxswains. Problems occur when rowers become overly distracted with external cues or become overloaded with internal cues (perhaps due to anxiety). Horsley advocates that rowers need to practice calming their minds and develop strategies to focus on appropriate cues. He suggests using both off-water and on-water concentration drills.

During unsuccessful performances, athletes may have programmed their own failure through self-doubt and negative statements. They are looking for an excuse for their potential poor performance telling themselves they don't row well in a cross wind, the rigging is wrong, or they ate the wrong food. To overcome this self-doubt, Johnson (1989) recommends techniques of self-talk, countering, thought stopping, and visualization.

Nideffer (1981) is another advocate of attentional control training in sports psychology. He recommends a technique that focuses concentration on the internal center of gravity of the body. He asserts that the average individual can be taught to control the inter-relationship between thought processes, centering attention, and physiological arousal.

Butler et al (1993) advocate "performance profiling" as a means of facilitating an understanding of the way an athlete perceives his/her ability and preparation for performance. Although the sport they studied was boxing, performance profiling addresses what they consider two fundamental aspects of applied sport psychology: self-awareness and goal setting.

Another psychological challenge in sports is to learn how to win after previously winning. Kreiner-Philips and Orlick (1993) studied the effects of success on world champion

athletes in seven sports (not including rowing). The athletes they interviewed fell into three categories: 1) those that followed success with repeated success, 2) those that declined but later repeated their success, and 3) those that were unable to repeat their success. All three groups were reported to be similar in the mental focus they carried into their first world championships, but there were major differences in the manner in which they focused in subsequent competitions.

The Continued-Success Group entered their next competition with the same focus they had during their previous win. They were confident in their ability to win and were able to connect in a way that allowed them to perform on “autopilot.”

Both the Decline-and-Comb-Back Group and the Unable-to-Repeat Group changed their focus in their next competition towards outcomes rather than the process of performing. They reported being focused on high expectations, not being clear minded, and trying too hard.

All groups felt increased demands and heightened expectations, but only the Continued-Success Group reported being able to maintain normal training and rest. This group also consistently attributed their continued success due to a mental component that included having a game plan, staying focused on the task, keeping things in perspective, enjoying the sport and new challenges, and maintaining good physical conditioning together with a positive outlook.

Joy (2005) advocates a scheduled yearly mental training cycle to include five meditative training techniques: quiet sitting, visualization, relaxation, concentration, and mindfulness. Joy believes these meditative practices should be practiced both on land and on the water beginning with the first practice, and that this training leads to “flow” (analogous to swing) and peak performance. According to Joy, “Mental training enhances the flow and power of physical

movement by allowing efficient release of energy.” It involves “a total integration of body movements with the shell, blades, and water, along with a heightened awareness and concentration.”

Joy witnessed the power of this technique in 1984 as practiced by coach Neil Campbell with the Canadian men’s eight in winning the Olympic gold medal. He attributed their oneness of body, mind and spirit to allow these rowers to relax, focus, and enjoy the competitive moment.

*Without training, they lacked knowledge.
Without knowledge, they lacked confidence.
Without confidence, they lacked victory.*

Julius Caesar

Decisions: Strategy and Race Plan (S)

A classmate once asked, “What is there to learn about rowing strategy other than to just pull hard?” To an untrained eye, there would appear to be no strategy at all to a 2000-meter sprint. The coach trains the crew to begin with a racing start, lower its stroke rate to a sustainable rate in the middle 1000 meters, and then sprint at the end of the race. If the crew pulls as hard as it can and executes its coach’s stroke rate pacing plan, the crew should finish in its optimum race time. Theoretically, it is just that simple.

Coaching Philosophies

US national team coach Mike Teti is an expert on racing strategy having coached the US men’s eight to the Olympic gold in 2004 (the first US gold in the eight since 1964) and then repeating as the world champion in 2005. According to Teti and Nolte (2005), strategy is a skillful plan to reach a goal, and tactics are the means to implement the strategy. They believe a coach needs to use any information available about their competitors in order to create a winning strategy. A coach also must consider many other factors including the importance of the race, the level of competition, and even weather.

However, they consider the most important factor in choosing a race strategy is to adapt the race plan to your athletes and to set realistic goals. When adapting your strategy to your crew and setting realistic goals, Teti and Nolte assert, “Winning a bronze is much better than racing for victory and coming in fourth.”

In training for competition, the crew should already have figured out the crew’s most effective stroke rate. According to Teti and Nolte (2005), the adrenaline that comes with a major

race may cause the crew to row higher than planned. If the crew is within one stroke per minute of plan, they believe no adjustment is needed. If off by more than that, an experienced coxswain should then make an adjustment.

Teti and Nolte (2005) believe that a race plan should reflect not only technical and physiological capabilities, but also psychological strategy. Rowers often say their most memorable race is when they rowed an even pace at the beginning of the race and then rowed through the competition to win at the end. Nevertheless, Teti and Nolte believe in the racing philosophy of a fast start and trying to take the lead early. They advise that you always need to stay with the leaders because it is difficult to get big margins back. They also suggest that a crew that gains a one-length lead by the 1000-meter mark can “get brave” knowing they only have to hang on to their lead for another 2 minutes and 38 seconds.

Racing information on your opponents is available in terms of official results and 500-meter splits. Stroke rates can be taken from the shore. Teti and Nolte (2005) believe, “You have to interpret and use this information to the best of your ability.” Split times give coaches an idea of competitor speed distribution throughout the race. Because other coaches also study race results, Teti and Nolte favor using different race profiles in the heats and the finals so as to throw off those competitors who are studying them.

Gearing and Pacing Strategy

Hydrodynamic resistance to the flow of the boat is a function of skin drag, form drag, wave drag, and forces resulting from poor technique (Jones and Miller, 2002). The predominant source of resistance is shell skin friction with the water. The laws of fluid dynamics show this

skin friction to be proportional to the velocity of the boat squared while the metabolic power consumed in moving the boat is related to the velocity of the boat cubed (Secher, 1993).

Consider an example by Nolte (1991) calculating the water resistance effects of maintaining a constant velocity of 5 meters per second compared to a speed distribution that spends half the time at 4 meters per second and the other half at 6 meters per second. Although both of these scenarios average 5 meters per second, the latter results in 4% greater boat resistance.

Thus, the metabolic cost to the rower is minimized by maintaining a constant boat speed. This would encourage race strategies that maintain a constant speed over the course of a race while minimizing or eliminating racing starts and sprints. Greater hydrodynamic resistance could also argue against the use of Big-10 drives due to the extra energy needed to increase velocity while making a temporary drive in the body of the race.

Mechanical gearing is part of the overall race strategy as planned by the coach. For longer races or for races to be rowed at higher stroke rates, the gearing leverage can be lightened to reduce the work per stroke and thus balance the physiological energy expended according to the capabilities of the rowers, the expected time duration of the race, and the planned total number of strokes.

In spite of the non-linear effects of hydrodynamic drag, the goal of crew racing is to row at the fastest overall average speed so as to achieve the fastest time possible. Effectively using all of the available anaerobic and aerobic energy resources argues against using a constant speed throughout a race. Furthermore, the race plan must factor in the psychological advantages of leading in a race or staying within striking distance of the leader.

Strategy Profiles

Klavora (1979) defines the basic principle of the even-pace strategy is to start at the highest stroke rate that can be sustained throughout the race so that the last remnants of energy to reach the maximum possible oxygen debt is used up in the last stroke of the race. The crew would begin with a moderately fast start, quickly settle into an optimal racing rhythm, and would not sprint at the end of the race.

According to Klavora, although an even-pace strategy has been proven by physiologists to be the most economical, it is very hard to achieve in actual practice. He cites examples of world championship crews that demonstrated an even-pace strategy. The even-pace strategy was demonstrated based on their official 500-meter split times. However, his data do not show whether the crews actually took a racing start or a finishing sprint. Nevertheless, he concludes that, “it is obvious that whenever even pacing has been followed it has brought success to crews employing this racing plan at an elite level of competition across a variety of events.” He goes on to explain that the even pace strategy may work better at the highest level of competition because such crews know their physical capabilities perfectly, and it takes years of experience to learn to row at a consistently even pace.

Kennedy and Bell (2003) studied the spontaneous pacing strategy of individual male and female rowers, both before and after 10 weeks of a typical off-season training program. Subjects completed a simulated 2000-meter race using ergometers. Their only guidance was to row as fast as possible using their own race strategy. Velocities were recorded at every 200-meters of the simulated race. Their findings showed that the fastest male rowers adhered to the constant-

pace model, especially after training. By contrast, the fastest female rowers, after training, employed more of an all-out strategy to take the lead early while showing large deviations from mean rowing velocity. The sample sizes for this study were small, but it is significant that this research provided distinct profiles of race strategy using only 200-meter splits.

Using onboard monitoring devices such as the Nielsen-Kellerman SpeedCoach, it is possible to record very detailed information about your own crew. Most crews would not use this technology during a race because of the extra weight and the extra water resistance of the impeller underneath the shell that records boat speed. However, using such onboard technology, racing velocities can be tracked at levels of granularity much more detailed than just the 500-meter split times officially reported. According to Teti and Nolte (2005), this more detailed analysis reveals the “tactical moves of the crew” as well as performance “problem areas.” Teti and Nolte consider this type of detailed speed analysis to be valuable for the crew and their coach, but lament that “you can’t see the same analysis of the other crews.”

Pacing studies have been published (Garland, 2005) that examine how velocities vary among the four 500-meter quartiles of race. As would be expected, the first 500-meter split is almost always the fastest since it contains racing starts at a high stroke rate. The last 500-meter split is generally the next fastest quartile since it contains the finishing sprints of competitors. Garland found that compared to the average velocity over the 2000 meters, the quarterly splits show relative velocities of 103.3%, 99.0%, 98.3%, and 99.7%. However, these patterns do not isolate the pacing and speed effects of racing starts and final sprints (roughly 250 meters each). Starts and sprints are blended into the results of the 500-meter segments. Unfortunately, race results are not reported for 250-meter intervals.

Another study (Kleshnev, 2001(1)) examined 12 “patterns of race strategy” defined as the quartiles where crews are at their fastest and at their slowest relative to the other crews, and the relationship of this fast-slow pairing to how well the crews finished in the race. For example, a 1-4 pattern means the crew performed its best relative to the other crews in the first 500 meters and performed its relative worst in the last 500 meters.

Kleshnev summarized the placement of crews as a function of these quartile patterns. This approach reveals no single winning strategy, but patterns can be summarized by the frequency of success. Of the 12 possible patterns of fastest-slowest quartiles, the 4-1 pattern (fast finish and slow start) produced the most gold medalists (4 of 13), yet eight other patterns also yielded gold medals. The 4-1 pattern also yielded one last place finish. Kleshnev updated his study in 2003 and extended it to 10 years of championship history (Kleshnev, 2003). This showed all 12 race patterns resulting in crews finishing in all 6 positions, but this time with the opposite 1-4 pattern (relatively fast start and slow finish) yielding the most gold.

The current state-of-the-art in race strategy modeling leaves many questions unanswered about detailed race dynamics, the situational motivation and effort of winning and losing crews, and the validity of comparing the statistical performance of winning crews against the performance of crews that are hopelessly out of contention. What is unexplored in all of these studies are the timing and dynamic effects of drives and counter-drives as crews execute tactical moves to try to gain or hold the lead.

*More than anything else,
it was our carefully defined strategy that helped us win the championship.*

Mike Teti
(Teti and Nolte, 2005, p.247)

Decisions: Tactics and Contingencies (T)

Strategy decisions are made by the coach before the race in the form of a race plan. The coach drills this race plan into the crew – possibly allowing for race contingencies. The coxswain serves as the “agent” of the coach in executing the race plan. Tactical decisions are made by the coxswain during the race – either closely following the race plan or making tactical adjustments on the fly depending on the contingencies the crew experiences during the race.

Responsibility for the Race Plan

Crews usually begin with a racing start for roughly 250 meters and then settle to row the body of the race at a lower stroke rate. Most crews will call up the stroke rate with about 500 meters to go, and finish with a full sprint over roughly the last 250 meters.

Yasmin Farooq is a former world champion coxswain for the US women’s eight. In Table 2-8, she summarizes a sample race plan (Farooq, 1992) along with the goals she would communicate to her crew at each phase of the race:

Tactics may include Big-10's or drives at one or more points in the race to try to make a move on the other crews. Drive tactics vary from coach to coach. Some do not use them – preferring that the crew row at a steady level of effort throughout the body of the race. Other coaches plan one or more drives lasting 10, 15, or 20 strokes each. Other crews plan to take drives at the discretion of the coxswain as circumstances seem to warrant -- often to achieve a psychological effect to inspire your own crew and to discourage your opponents.

Table 2-8: Sample Race Plan (Farooq, 1992)

First 500 meters:

- 5 strokes at stroke rate of 48 with a goal of building boat speed and lengthening to full slide.
- 30 strokes at 44 stressing rowing light, quick, efficient, and to breathe.
- 20 strokes at 40 while increasing spacing using body swing.
- 20 strokes at 38 while increasing spacing using leg drive.

Second 500 meters:

- The crew should be rowing at 37 strokes per minute.
- At some point, take a power 10 for “connection and explosiveness.”

Third 500 meters:

- At some point, take a power 15 for “horizontal swing” while shifting up the hull speed.

Final 500 meters:

- 20 strokes at 38 with a goal to build the energy with each shift, accelerate the boat, and keep length.
- 20 strokes at 40.
- 20 strokes at 42 with concentrating on matching body swing, sitting up but keeping full slide, and catches.

At the 2007 US Rowing Convention I asked Mike Teti (coach of the 2004 and 2005 US gold medal 8) if it is a good idea for a crew to take a Big-10 type drive. He responded that it all depends on the coach and the crew. I asked Pete Cippolone (coxswain of the 2004 US gold medal eight) at the 2005 US Rowing Convention how he decides when to take a Big-10. He responded that he would never dream of taking a Big-10 unless it had been preplanned before the race, but that they usually take a single drive at the 1000-meter mark. According to Teti and Nolte (2005), special bursts are only effective if they are a decisive attack that changes the race. They believe that a Big-10 is not long enough, that a Big-20 is too long, and that a 15-stroke burst is best in order to make a difference in the race.

Coxswain Duties

According to Farooq (1992), the coxswain has five primary duties:

1. Steering
2. Technical coaching (assisting the coach)
3. Help practices to flow smoothly
4. Motivating the crew and teamwork
5. Racing and strategy

According to MacDonald (1980), the coxswain's job is to implement the race strategy that has been formulated by his coach. If the race does not go according to plan, the coxswain may have to formulate and alter strategy in the midst of a race. In this case, MacDonald compares the role of the coxswain to that of a quarterback calling an audible at the line of scrimmage.

When your own crew is moving on the competition, MacDonald cautions that the coxswain must describe that movement in a way that guarantees it will continue. He states that coxswains can actually destroy movement by getting the crew so excited that the rowers lose their sense of pacing and begin to rush. When the other crew begins to move on you, MacDonald describes the coxswain's challenge as to prevent the crew from panicking and to find a solution to the internal problems that may be hurting performance. In any case, the coxswain should never lie to the crew or his/her credibility is lost forever.

Although the coach's race strategy is drilled into the crew, teams rarely practice adapting to unexpected deviations from strategy, such as how to adjust the stroke rate after settling at the

wrong pace after the racing start. Likewise, unexpectedly trailing or unexpectedly leading in a race present new race scenarios for the coxswain to consider and for which the coxswain should be prepared to make adjustments. McArthur (2005) cites an example of one of his crews unexpectedly finding themselves in front of the rest of the field by a wide margin. It was such a shock to them that they did not know what to do, and so they never really settled into the race, and were overtaken by the other crews in the last 500 meters.

The judgment needed to deal with unplanned contingencies requires situation awareness, the courage to act independently, and the experience to know how to adjust race tactics and perhaps even adapt to an entirely new race strategy. The coxswain must know the options available to him and be able to assess the relative risks from deviations from plan. Tactics include adjusting stroke rate, taking Big-10 drives, and communicating effectively to the crew to adapt to circumstances while keeping them motivated.

It was Farooq's experience that before each race, the crew would map out its race strategy. They would also plan a backup strategy in case the crew is not where it should be at a certain time. Everyone (coach, rowers and coxswain) knows the backup before the race begins.

Farooq also advises that your arsenal of motivational and technical tactics should include only a few key points in the race where you want to make moves on the competition. Most moves are decided and discussed days or even weeks before the race between the coach and team. Together, the team discusses the technical focus for each move and sometimes the motivational focus. Rarely are more than two moves planned for a race, but that leaves the coxswain the flexibility for spontaneous moves on the competition.

Farooq describes one move they used in the 1990 world championships. They labeled this the “flex” as an abbreviation for flexing a little muscle. It was meant to be the best 10 strokes of their race and was used only once per race. It was also exercised only once each practice.

Coxswain Training and Programming

The coxswain’s tactical decisions during a race depend on developing an eye for race strategy. The coxswain needs to understand the possibilities in any given race situation – his “situation awareness.” This is gained through racing experience, but is totally lacking in an inexperienced coxswain. The coxswain must also develop an eye for judging race positioning based on the angles of the other crews, the position of buoys, and the continuously varying dynamics of crew speed and shell motion. Theoretically, simulation training could help accelerate the coxswain’s learning curve by providing the opportunity to gain virtual race experience and to better read viewing angles, movement dynamics, and shell speeds.

Rowing is generally thought of as a sport for rowers who athletically compete in a racing shell using a combination of strength, skill and endurance. Often overlooked is the role of the coxswain who is responsible for controlling the race by directing the crew and navigating the shell. The coxswain steers the shell down the course. He/she also shouts the tactical commands such as stroke rate changes and power-10’s that implement race strategy.

The role of coxswain is analogous to an airplane pilot in several respects. Both pilot and coxswain must control a complex vehicle in a strange environment. Coxswains, like pilots, need to develop situation awareness to learn how to interpret the unnatural environment in which they

find themselves, and also to develop a sense of the competitive tactical opportunities possible. They must perform well under stress dividing their attention among steering, perceiving their circumstances, strategizing, and communicating.

If every race went according to plan, the coxswain would have little to decide. However, similar to unplanned aircraft emergencies, unusual circumstances arise during races (or practices) for which coxswains may have never actually trained, and perhaps have never even previously considered. Some examples of unplanned rowing emergencies include:

- Broken equipment and other irregular circumstances in the first 100-meters of a race where the race can be stopped and restarted – provided the coxswain knows how to signal the referee.
- Catching a “full crab” where a rower loses complete control of his oar. The crew may need to stop before the oar can be recovered and the race resumed.
- Large wake from a powerboat approaching and threatening to capsize a shell, damage equipment, or merely surprise the rowers.
- Race course debris partially blocking a lane, or unfamiliar bridges and turns that must be efficiently navigated.
- Competitive situations may arise that do not match the race plan (i.e. unexpectedly trailing in a race or unexpectedly rowing at the wrong stroke rate).

These circumstances match the two “crisis decision making” training objectives defined by Sniezek et al (2001) that justify advanced simulation training. First, crises are rare, making it difficult to acquire direct experience. Second, when crises do occur, conditions are unfavorable

for training. In the midst of a race, the coxswain does not have the opportunity to practice or redo his mistakes. Although there will be other races, there is only one chance to execute any single race correctly. Simulation training for unusual circumstances and competitive situations can help. Sometimes, staging these circumstances in a live practice is impossible. Simulation affords the opportunity for a coxswain to practice emergency procedures, interpret unusual race situations, and then receive coaching advice. It could also provide steering practice for a fast-moving, 60-foot racing shell down an unusual racecourse, sometimes pushed by unusual wind conditions and water currents.

In a sense, the coach's race plan is an attempt to program the crew to behave under a full range of circumstances. In simulation terms, the crew is the coach's "agent" and should behave as programmed. Carrying this metaphor further, a simple architecture for agent perception and planning is the use of a finite state machine. These are systems in which a finite number of states are connected by a graph of directed transitions. They are widely used in games and simulations because they are simple, efficient, deterministic, and easily understood (MacNamee, 2004). Their primary disadvantage is that for many applications, the task of mapping out every possible situational state can be overwhelming. However, this may not pose a major problem for crew races since there are only a limited set of viable stroke rate options. Figure 2-2 illustrates sample finite state machine architecture to represent the stroke rate perception and planning required of a coxswain, serving as agent of the coach.

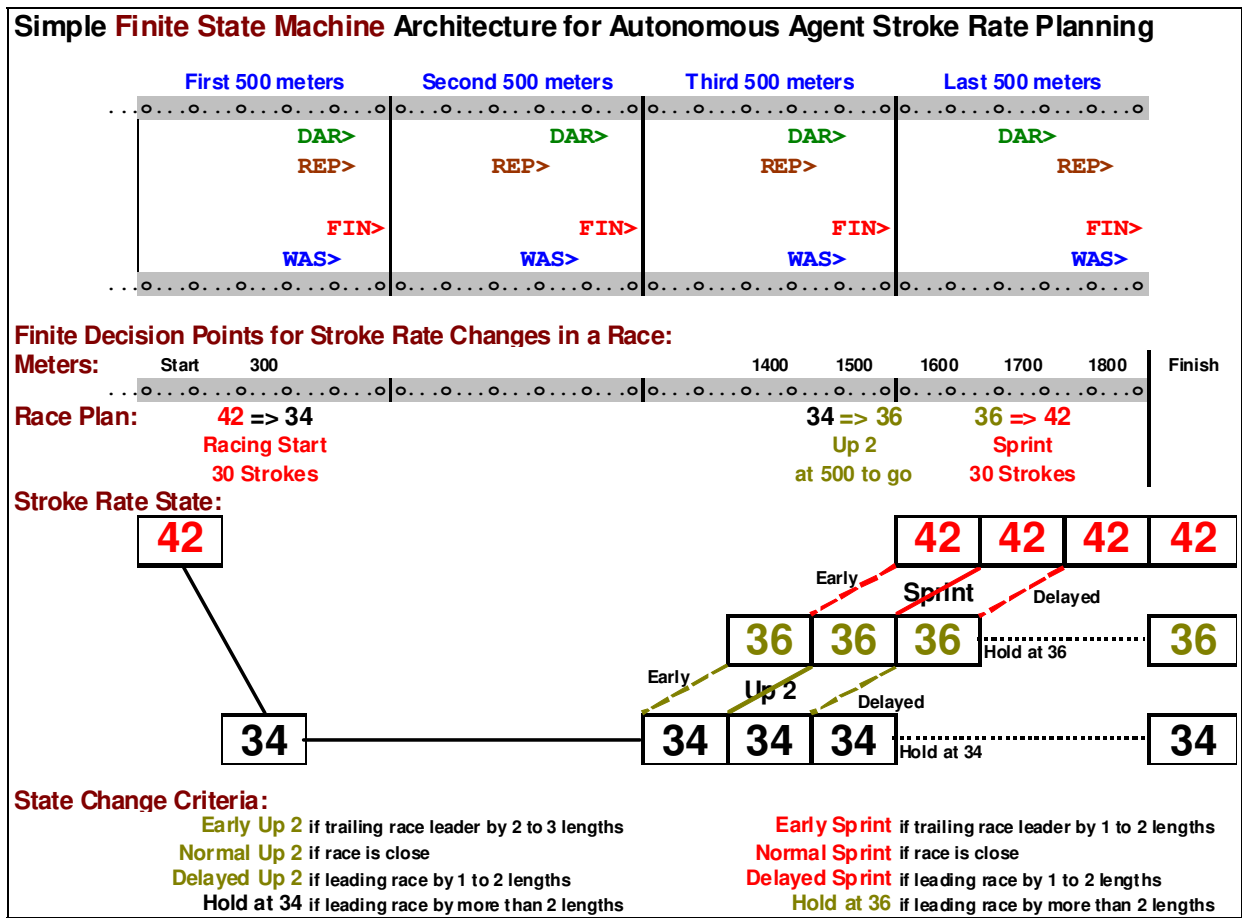


Figure 2-2: Finite State Machine for Stroke Rate Contingency Planning

The amount of leeway and judgment permitted a coxswain varies based on the coach's philosophy. Coxswains may have discretion as to when to call up the stroke rate at the end of the race – earlier or later than planned, and perhaps not even take a sprint at all if it is not needed. These tactics are available to the coxswain to experiment with and adapt to race circumstances, or the coach could instruct the coxswain to blindly follow the preplanned race strategy. Of course, if good crew race simulation models existed, then coxswains and coaches could train and experiment with race strategy and tactics in circumstances other than a live race.

Tactical Race Decisions

A crew typically uses a racing start for the first 20 or 30 strokes (roughly 250 meters) before setting down to cruising speed and finishing with a sprint. This is evidenced by studying the splits of world championship competitions including a recent study of the 2000 Olympics and 2001-2002 world championships (Garland, 2005). The pattern of results from his study show close consistency between the split times for men vs. women and for winning crews vs. losing crews. Compared to the average speed over the 2000 meters, the quarterly splits show comparative speeds of 103.3%, 99.0%, 98.3%, and 99.7%.

Garland's study included all of the qualifying rounds as well as the finals competition. Because qualifying rounds were included, he chose to include only those race results where there was evidence that the crews made a good attempt to complete the course in the shortest possible time. The data suggested that 41% of all regatta races should be excluded due to abnormal race patterns.

He interpreted two reasons for needing to exclude these races: 1) the crews overestimated their ability and set off at a pace that was too fast to sustain, or 2) there was a "deliberate tactical decision" to slow down to conserve energy for further rounds of the competition. He could not tell how often each of these reasons occurred, but one can assume any such deliberate tactical decisions were made as contingencies during the race due to the crew being comfortably ahead or hopelessly behind. In many race circumstances, it makes sense for losing crews to save their energy for their next race, and for winning crews to conservatively just sit on their lead without taking a full sprint.

Presumably, the remote risk of an execution error and the risk of exhaustion are reasons why a crew would not attempt to finish in the shortest possible time using a full sprint. At the 2006 US Rowing Convention, US national coach Mike Teti said that his 2004 men's eight Olympic champion crew did not take a full sprint while winning the finals race. Although the Dutch crew was closing on them in the last part of the race, there was not enough time left in the race for them to catch the US crew.

Coincidentally, this tactic was repeated from 40 years earlier, the last time the US eight won gold at the Olympics. Bill Stowe (Stowe, 2005), stroke of the 1964 US eight, explained his crew's decision not to call up the stroke while leading in the Olympic finals, "With 500 meters to go we were in control of the race and as the stroke I made the decision not to take the cadence higher. Why risk a crab? We had shown our potential sprint ability in our repechage against the Japanese but did not need to risk it here."

*Strategy without tactics is the slowest route to victory.
Tactics without strategy is the noise before defeat.*

...

To be prepared beforehand for any contingency is the greatest of virtues.

Sun Tzu
(The Art of War, 500 B.C.)

CHAPTER THREE: METHODOLOGY

The 8-factor Model of Crew Race Performance (Cornett et al, 2008) provides a conceptual framework for evaluating how crews perform against each other in a race. This model was used as a basis for structuring the literature review in Chapter Two. My dissertation research methodology is focused on the last two model factors dealing with strategy and tactics. In particular, my research measures performance parameters demonstrated in Olympic and world championship competitions. These parameters could be used to guide a coach's race plan as well as the tactical contingencies that coxswains must react to within a race.

Gaps in the Literature on How to Model and Visualize Race Results

How thoroughly race strategy and tactics can be studied is a function of the number of race performance observations recorded. Most local rowing competitions are reported with only one overall finishing time observation per crew. World championships report four quarterly 500-meter time splits. However, enormous additional performance detail can be mined from video records of world and Olympic championships.

Many important questions about race strategy and tactics are difficult to visualize when examining the typical results published on race results. Consider the example in Figure 3-1 that reports the results of the 2008 Olympic Women's Eights Final. As is customary in world championships, the times of each crew is reported at the four 500-meter quartiles. Based on these four observation points, the following information is summarized:

1. Cumulative race times for each crew at the four 500-meter quartiles.
2. The position ranking of each crew at each of these four points.

The Official Website of the Beijing 2008 Olympic Games August 6-24, 2008

COMPETITION INFORMATION

Schedules & Results Medals Athletes & Teams Background Records

Schedules & Results > Rowing > Women's Eight Final A

News Photos Videos

Results
Women's Eight Final A
SY Rowing-Canoing Park / Sun Aug 17 2008

Medals Reports

World Best Time:
USA SICKLER Brett / COOKE / GOODALE Anna / SHOOP Lindsay Eton (GBR) 2006 5:55.50

Rank	Lane	NOC	Name	500m	1000m	1500m	2000m	Qual. Code
1	3	United States	(b) <u>CAFARO Erin</u>	1:29.04 (1)	3:01.32 (1)	4:33.88 (1)	6:05.34	
			<u>SHOOP Lindsay</u>		1:32.28 (1)	1:32.56 (2)	1:31.46 (4)	
			(2) <u>GOODALE Anna</u>					
			<u>LOGAN Ella</u>					
			(3) <u>CUMMINS Anne</u>					
			<u>FRANCIA Susan</u>					
			(4) <u>LIND Caroline</u>					
			<u>DAVIES Caryn</u>					
			(5) <u>WHIPPLE Mary</u>					
			(6)					
			(7)					
			(8)					
2	5	Netherlands	(b) <u>DEKKER Femke</u>	1:30.62 (4)	3:04.95 (4)	4:38.59 (4)	6:07.22	
			<u>SHULDEBS Marlies</u>		1:34.33 (4)	1:33.64 (4)	1:28.63 (1)	
			(2) <u>KINGMA Nienke</u>	1.58	3.63	4.71	1.88	
			<u>REPELAER van OBIEL Boline</u>					
			(3) <u>van BUMPT Annemarijke</u>					
			<u>TARGEER Helen</u>					
			(4) <u>SIEGELAAR Sarah</u>					
			<u>de HAAN Annemiek</u>					
			(5) <u>WORTEL Ester</u>					
			(6)					
			(7)					
			(8)					
3	4	Romania	(b) <u>BURCIJA Constanta</u>	1:30.02 (3)	3:03.10 (2)	4:35.93 (2)	6:07.25	
			<u>SUSANU Viorela</u>		1:33.06 (2)	1:32.83 (3)	1:31.32 (3)	
			(2) <u>SERBAN Bodica Hada</u>	0.98	1.78	2.05	1.91	
			<u>BARBAS Enika</u>					

Figure 3-1: Competition Data Available for the 2008 Olympic Women's Eights Finals

3. Time splits or how long each crew took to complete each 500-meter quartile.
4. The relative ranking of each crew in terms of their quarterly time splits.
5. The seconds behind the lead crew at each quarterly observation point.

Quartile information is considerably more useful than just recording the total 2000-meter times of each crew. From quartile data, researchers have studied the quartile patterns that are typically the fastest (Garland, 2005) and in which quartiles winning crews tend to do better than their opponents (Kleshnev, 2001).

Nevertheless, analytical approaches to studying the patterns of quartile results leave many unanswered questions about race dynamics, including the timing and discrete effects of drives and counter-drives as crews execute tactical moves to gain or hold the lead. The strategy intention of crews is not necessarily reflected in how the crews performed by quartile when compared to the average speed of the other crews. Comparative stroke rate pacing patterns over the duration of the race has not been systematically studied for purposes of competitive strategy. This is largely because stroke rates are not reported at all in official race results.

Video records of world championship finals races are available for purchase, and can be used to perform a methodological and detailed decomposition of selected crew race physical criteria. From the much more detailed information obtainable from video records, new research designs can be developed to better answer the following types of questions?

1. Did the winning team lead the entire race, or at what point did they take the lead?

Challenger crews sometimes take a temporary lead within a 500-meter segment (especially in the first 500 meters) but may not be ahead at the quarterly split points.

2. Even after the winning team takes the lead, do any of their opponents put on a drive and mount a serious challenge for the lead later in the race. Quarterly results may reveal such patterns, although many challenge drives do not coincide with 500-meter splits.
3. What stroke rate pacing tactics were used by the crews, and do changes in relative stroke rates coincide with when the crews drive on each other? Stroke rate data is available by mining video records, but not at all available in official race results.
4. Is there any evidence that the winning crew had more energy left at the end of the race and could have even gone faster if necessary? Once a crew gains a decisive lead, it can sit on its lead without needing to extend it further. As the finish line approaches, winning crews can also afford to allow crews to close the gap a little – sometimes not even taking a final sprint if it is not needed.
5. Does it appear that any of the losing crews were “broken” in terms of their physiology or psychology? The rate at which a crew fades to another crew may accelerate once a crew is broken. This can occur late in a race and only for a portion of the final 500 meters.
6. How much a lead does a crew need to build before it is confident of holding off their nearest challenger? Studying the mix of leads won or lost allows for the computation of a “probabilistically decisive lead.” However, using only quarterly split data does not allow for a thorough analysis of how this probability varies over every portion of the race.

7. At what point in the race should a crew switch its focus from catching the crew in front of them to holding off other challengers behind them? Is there evidence that this ever happens? Based on a measure of what constitutes a probabilistically decisive lead, and after examining the detailed drive patterns in a race, race analysts can begin to interpret the dueling strategies of crews.

When trying to answer these questions using the standard race results summary, many of these questions are difficult or impossible to answer. With only four observation points recorded for a race (at 500-meter splits), there is a very limited amount and variety of information available for interpretation.

By comparison, the video-analysis of a crew race can mine from 10,800 observation points (360 second average race duration multiplied by the 30 frames per second video recording speed). The information that can be collected from video analysis is 1000 times more detailed than the quartile splits officially posted as world championship race results.

Research Hypothesis

A methodological and detailed decomposition of selected crew race physical criteria can produce performance parameters useful in modeling situational performance and evaluating optimal strategies.

Researching this hypothesis addresses gaps in the literature that can be attributed to:

- Insufficient physical observations as reported in official race results.

- Suboptimal race models based on analyzing the fastest parts of the race rather than models based on analyzing the most decisive parts of the race.
- Not knowing what constitutes a “decisive lead” as a basis for strategy decision-support and post-race performance analysis.

A methodological and detailed decomposition of race results should include an examination of the “drives” crews make on each other in a race. The situational performance of these drives can be further researched through the development of a generic drive model.

Research Scope

The races studied in this dissertation are the five championship eights races from the 2004 Olympics and 2007 World Championships. Video records of championship finals races (but not the preliminary events) are commercially available on DVD. Therefore, the analysis is limited to crews capable of performing at an “elite” level of competition and in the most important races possible with world championship and Olympic medals at stake in these finals races.

Although there are many other boat classes in these regattas (including singles, pairs and fours events in 1-oared sweep and 2-oared sculling classes), only eights competition is studied here. The races studied are limited to 8-oared world championship competition including two men’s, two women’s, and one lightweight men’s competition. Patterns of results for other boat classes may demonstrate similar principles, although that presumption remains for future research to explore. Results are not stratified between men’s, women’s, and lightweight eights classes of events. With a much larger study, it is possible, but remains untested, that meaningful variations by gender and weight class could be observed.

The research data studied includes the patterns of relative positioning over the 2000-meter race course, drives crews make on each other, stroke rate pacing, and final placement performance results. Performance is further assessed in terms of the probabilities of success as a function of the lead that one crew holds over another in the various duels between pairs of crews.

A spreadsheet model was used to dissect the details of actual race performance as measured from video race recordings. The spreadsheet model is named EEVA – an acronym for the functions it serves in Extracting race results, Extrapolating missing information, Visualizing race dynamics, and Analyzing race data. The successful use of this EEVA software demonstrates the feasibility that thousands of video observations can be efficiently extracted and effectively analyzed from video recordings. The actual design of the software used to evaluate and visualize race results is outside of the scope of this dissertation research. These software tools are considered proprietary, and the calculations are too intricate to easily summarize. However, some of the complexities of video extraction and analysis are discussed where it has a bearing on the quality and quantity of data that can be mined from video records.

Mining Data from Video Records

The following steps outline the overall approach taken to mining video crew race data:

1. Develop a custom EEVA (Extract, Extrapolate, Visualize, and Analyze) spreadsheet system as the primary data tool for video-based crew race data mining and research. EEVA includes a variety of valuable features:
 - a. Race Observation Event Log (ROEL).
 - b. Tools for reconciling observed data with official split times.
 - c. Adjustment features to correct for defects in the video recordings – including blind spots, video gaps, and camera angle time shifts.
 - d. Graphical and algebraic tools to highlight inconsistencies to be checked that could be due to data entry errors.
 - e. Extrapolation tools to convert all race data for loading into a race results database using consistent 10-meter interval observations.
 - f. Tools for analyzing, modeling and graphing results.
 - g. Interface tools that allow race results to be exported to digital reenactment tools including Excel click-through race replays and a VRML (Virtual Reality Modeling Language) fly-through race replay immersive environment. (Digital reenactment tools have been prototyped but are outside the scope of this dissertation.)
2. Extract data from five championship video race recordings:
 - a. Load each video into Adobe Premier Elements (version 4.0) video editing software. This allows races to be easily navigated and paused frame-by-frame to identify the exact timing of race events at 30 frames-per-second precision. Each race is recorded

- into a separate video file while trimming data from other races, and appending two files together when the video for a race spans two digital files.
- b. Bookmark the videos for major race events to allow for easy navigation, data recording, buoy position modeling, and race data reconciliation.
 - c. Compare the data extracted from detailed video analysis versus the official race results reported as 500-meter race splits. Discrepancies can be corrected either by editing the video for recording gaps, or corrected through ROEL adjustment tools.
 - d. Initialize a buoy spacing model into ROEL so that the exact position of each buoy marker is identified (or at least estimated) and placed within the spreadsheet modeled course.
 - e. Gather frame-by frame detailed data (measured in 100ths of a second) from video race records using the custom ROEL software (Race Observation Event Log). Record every discernable buoy hit and every observable catch for each crew.
 - f. Identify the exact frame location of each camera angle shift in the video. Using calculated stroke rate intervals, construct a model of video transmission time shifts to adjust for gaps and overlaps in video records due to camera angle changes.
3. Modeling and analyses from the EEVA database:
- a. Each race is recorded into a separate ROEL spreadsheet. Once race record-keeping and modeling adjustments are complete, copy the race results data summary (extrapolated to 10-meter intervals) into the consolidated EEVA database.
 - b. The EEVA software calculates most of the modeling points defined in the generic drive model. However, Hold points and Challenge points must be subjectively

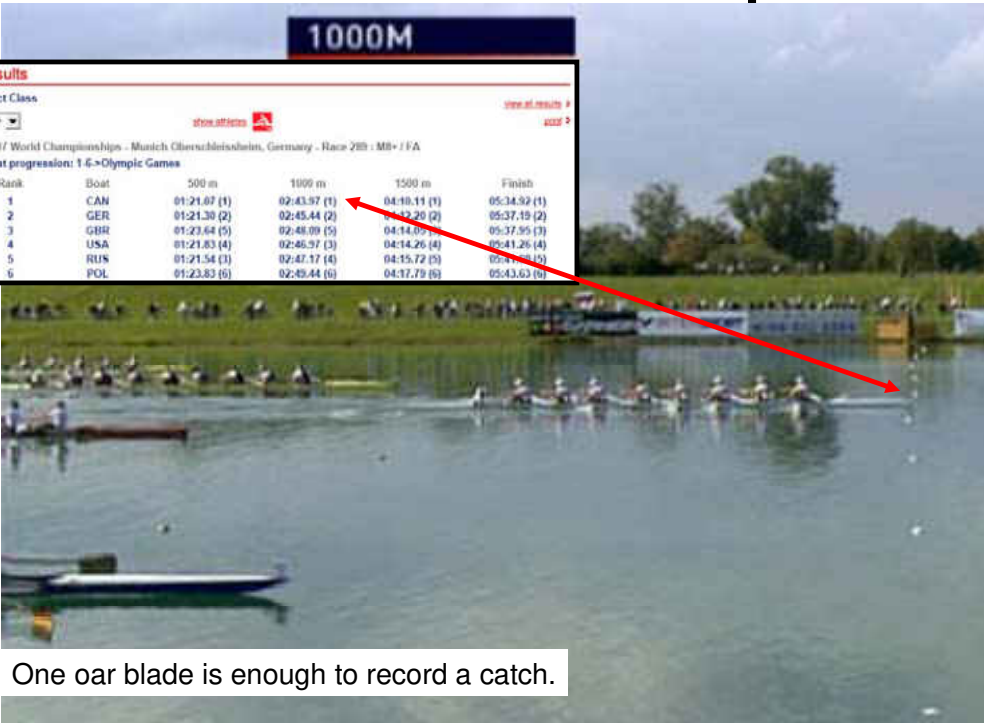
identified by the race analyst based on whether they appear to be acceleration points where the drive slopes seem to have shifted.

- c. Display and print out the numerous analyses, graphs, and models for which the EEVA software is designed to visualize and analyze.

Data Quality Issues Associated with Video Race Records

DVD videos of world championship and Olympic rowing finals are available for purchase as licensed by FISA, the world rowing governing association. Videos are available for races starting in 2002. Recorded at 30 frames per second, a six minute race contains 10,800 images, each of which can be analyzed for its information content with photo-finish precision.

Video Data: Observe up to 200 buoy hits and 230 oar blade catches per crew



1000M

Results

Select Class: M8+ [show athletes](#) [www.ri.results.fr](#)

2007 World Championships - Munich Oberschleißheim, Germany - Race 288 : M8+ / FA

boat progression: 1.G->Olympic Games

Rank	Boat	500 m	1000 m	1500 m	Finish
1	CAN	01:21.67 (1)	02:43.97 (1)	04:10.11 (1)	05:34.92 (1)
2	GER	01:21.30 (2)	02:45.44 (2)	04:12.20 (2)	05:37.19 (2)
3	GBR	01:23.64 (5)	02:48.09 (5)	04:14.05 (3)	05:37.95 (3)
4	USA	01:21.83 (4)	02:46.97 (3)	04:14.26 (4)	05:41.26 (4)
5	RUS	01:21.54 (3)	02:47.17 (4)	04:15.72 (5)	05:41.55 (5)
6	POL	01:23.83 (6)	02:49.44 (6)	04:17.79 (6)	05:43.63 (6)

One oar blade is enough to record a catch.

Figure 3-2: Buoy Hits and Oar Blade Catches Observable from Video Data

Two types of raw data observations (buoy hits and oar blade catches) can be recorded from video records with great precision (see Figure 3-2 for an example):

1. **Buoy Hits:** The exact frame at which the bow of a racing shell reaches a buoy marker. This provides a precise measure of the progress of crews down a course, and the relative distance between crews as they hit each of these markers. Buoys are typically spaced at either 10-meter or 12.5 meter intervals. This provides for up to 160 to 200 buoy hit observations per crew.
2. **Catches:** The frame at which the oar blades of a crew are just entering the water. Comparing the timing between catches, each crew's stroke rate pacing (measured in strokes per minute) can be measured throughout the race. At an average of 38 strokes per minute, a 6-minute race would allow up to 228 catches to be recorded per crew.

Mining data from video records presents some unique technical challenges:

1. **Blind Spots:** These are portions of the race where the camera angle does not allow all crews to be observed. Blind spots commonly occur when a crew has fallen far enough back that they can no longer be seen in the camera. Another occurrence for a blind spot is when the camera shows a close-up of one single crew (see Figure 3-3). For the five races studied in this research, Appendix A calculates the average frequencies over the 2000-meter distance of buoy hit blind spots and stroke rate blind spots.
2. **Time Shifts:** When switching between cameras, there may be a fraction of a second delay in the transmission of the video. For instance, video records can be time-shifted when switching views between a camera closely following the race from a trailing boat on the water and another camera recording from a tower on shore or even an

aerial view from a helicopter or blimp. The effect of a time shift can be to create short gaps or short overlaps in video race coverage. These gaps of up to one third of a second are not noticeable to the naked eye when watching a video, but are huge time shifts when recording observations at a level of precision of 30 frames per second (29.97 frames per second to be exact). The effect of correcting for video time shifts on calculated stroke rates is illustrated in Appendix B. (The mechanics of how the EEVA software adjusts for time shifts is beyond the scope of this dissertation.)

Video Data: A “blind spot” at frame 2726 (but a catch is still observable)



Camera angle close-up of the USA women at the catch at an extrapolated 92 meters (frame 2726) into the race on their way to winning the 2007 world championships. Viewing fans will enjoy this impressive image, but we lose valuable data observations.

Figure 3-3: Example of a Blind Spot in Video Race Recordings

3. **Missing Video:** Sometimes, videos are not complete records of the entire race. Television broadcast coverage frequently edits out the “uninteresting” portions of a race. However, short gaps can also occur from post-race video editing, or when races are recorded and replayed from two separate video files streamed back-to-back during replay.
4. **Reconciliation with Official Times:** The finishing times of championship crew races benefit from photo-finish recording devices. However, the 500-meter splits are often recorded through manual stop-watch technology by race officials. This introduces human error of up to plus or minus one-half second per crew. Sometimes, even the order of the crews is misreported (see Figure 3-4 for an example). Video analysis allows for more precise and accurate record-keeping – assuming the crews are in camera view and also assuming the buoy markers at the 500-meter points are precisely placed.
5. **Irregular Buoy Spacing:** Buoys may not be precisely spaced along the course. For example, at the 2004 Olympics, the buoys between 500-meter markers (although regularly spaced at 12.5 meter intervals) were not synchronized with the 500-meter buoys. Thus, their exact positions on the course had to be estimated (using the frame-by-frame race observations of calculated stroke rates and velocities). Inaccurate spreadsheet modeling of buoy placement can lead to wide fluctuations in calculated velocities, yet has no adverse effect on the calculation of stroke rates or time gaps behind the lead crew.

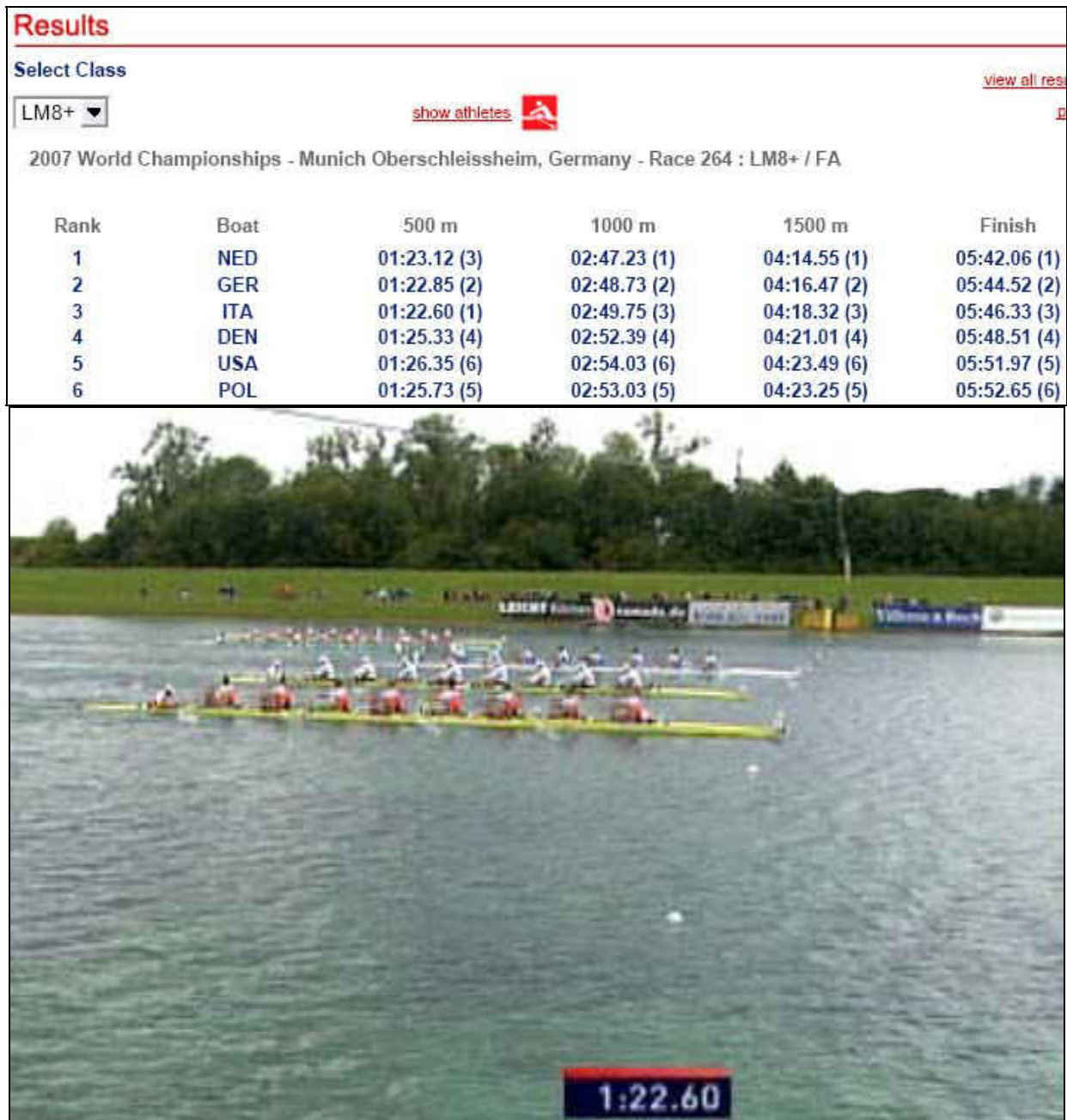


Figure 3-4: NED (foreground) appears to be in First (not Third) at the 500-meter mark (2007 LM8)

These technical challenges have all been addressed through custom software designed to model, extrapolate and reconcile the missing pieces of race data. The software is named EEVA (Extract, Extrapolate, Visualize and Analyze). The software is also helpful in detecting

transcription errors and dealing with the imprecision of selecting and recording the exact frame at which crews hit buoy markers or make a catch. Ultimately, every recorded event must reconcile with the official finishing times of each crew (but not necessarily the official split times) and account for every video frame or fraction of a second within plus or minus .03 second precision. Reconciliation is also aided by the fact that crews cannot take half strokes, nor will crews dramatically accelerate or change stroke rates by great amounts.

To assist in race analysis, the EEVA software extrapolates all race observations into 10-meter intervals, so that each crew has 200 calculated times and stroke rates for each of the 10-meter intervals throughout the race. These extrapolations are recorded into a single database that allows a variety of calculations, models and graphical comparisons to be systematically performed across crews within the same race. It also allows comparative visualization and modeling to be made across races.

Visualization of Relative Performance

The relative performance of teams can be graphically visualized as shown in Figure 3-5 for the 2004 Women's 8's finals. The graph shows the distance (measured in seconds) each crew trailed the leading crew – recorded at every point that a crew can be seen to reach a buoy in the video. Therefore, every point graphed is a direct observation. Blind spots are not shown as points on the graph. However, the line graph connects the observed points thus extrapolating all the missing points in the race. Since all the frames and fractions of a second must be reconciled in this continuous race record, the overall pattern of relative distance behind the leader is recorded to a high degree of precision and accuracy. Only when there are very long blind spots where a crew cannot be seen in the video are these linear extrapolations missing useful race detail.

When studying Figure 3-5, the timing of position changes can be easily observed. You can see where gaps are closing or extending between crews. Since all gaps are measured relative to the leader, the winning crew sits on the horizontal axis, while the distances between the first place crew and the others are easily observed in the graph. The distances between the five other crews and each other (dueling for positions 2 through 6) are observable, but more difficult to visually interpret in this graph.

Nevertheless, the graph illustrates that many dynamics are taking place during the race as crews drive on each other. Leads and positioning changes can occur at any point. All of the exciting things do not happen at the 500-meter points, or within discrete 500-meter splits. Therefore, race results recorded at this level of precision provide a much greater amount of useful information than just the official 500-meter split observations.

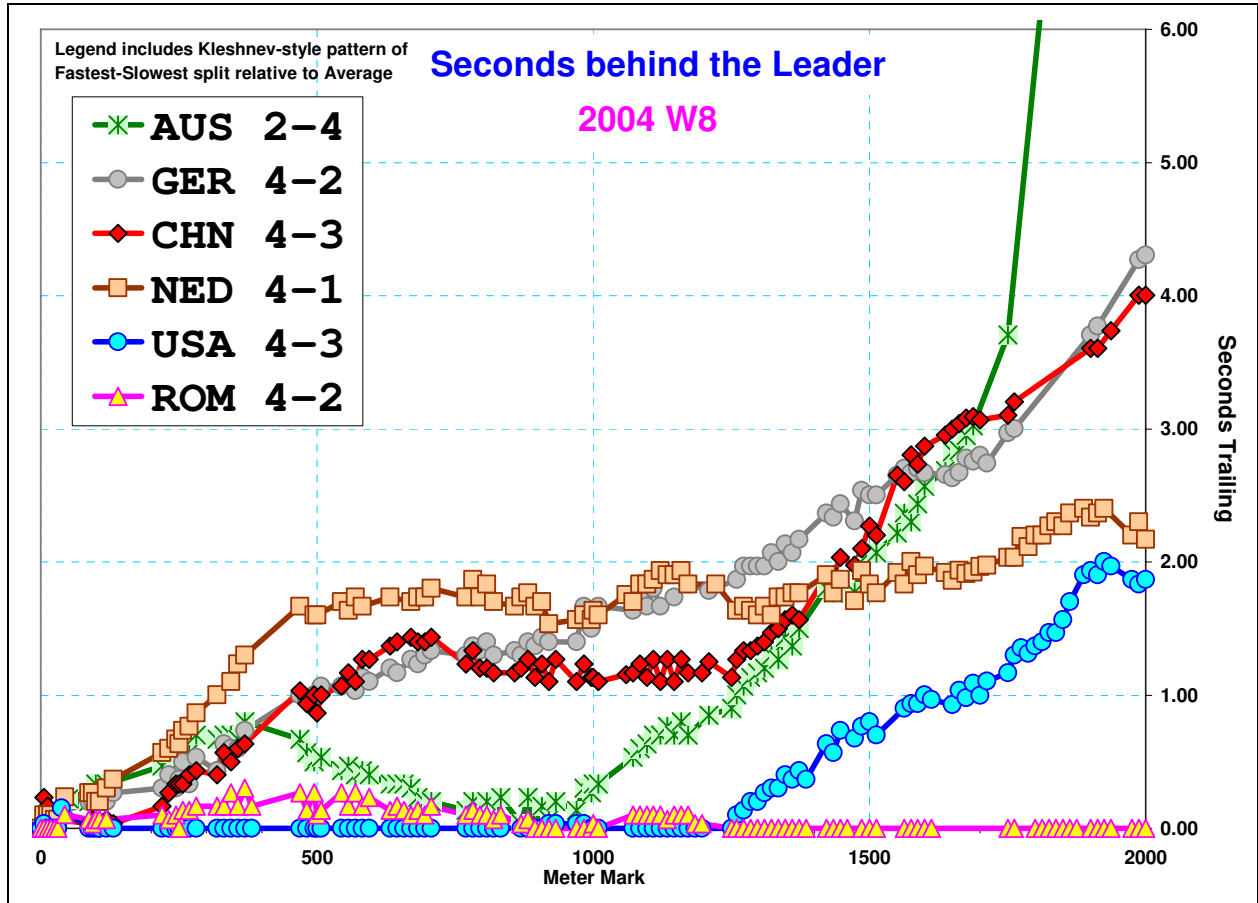


Figure 3-5: Relative Performance Summary

The legend also displays the Kleshnev-style quartile race patterns for each crew. In this race, the first five crews all had their fastest split in the last 500 meters relative to the average crew. This was because the Australian crew had an unusually slow last 500 meters (actually the last 250 meters). Whether this was due to an injury, equipment breakage, performance problem, or broken morale is unknown from the video because the last 250 meters was a blind spot for that crew. Kleshnev-style race patterns can be significantly skewed by the poor performance of a single crew. Graphical visualizations and models based on detailed video race analysis can

illustrate considerably more detail. Video records provide an enormous amount of potentially useful race detail to analyze for their insights.

Visualization of Stroke Rates and Relative Pacing

Tactical insights can be gained by studying the stroke rates of competing crews. Figure 3-6 shows the stroke rates of the 2004 Olympic women's gold and silver medalists. The camera view naturally follows the two leading crews throughout the race, thus enabling the timing of most catches to be recorded for these two crews. The black points on the graph are where stroke rates were extrapolated due to blind spots in the race.

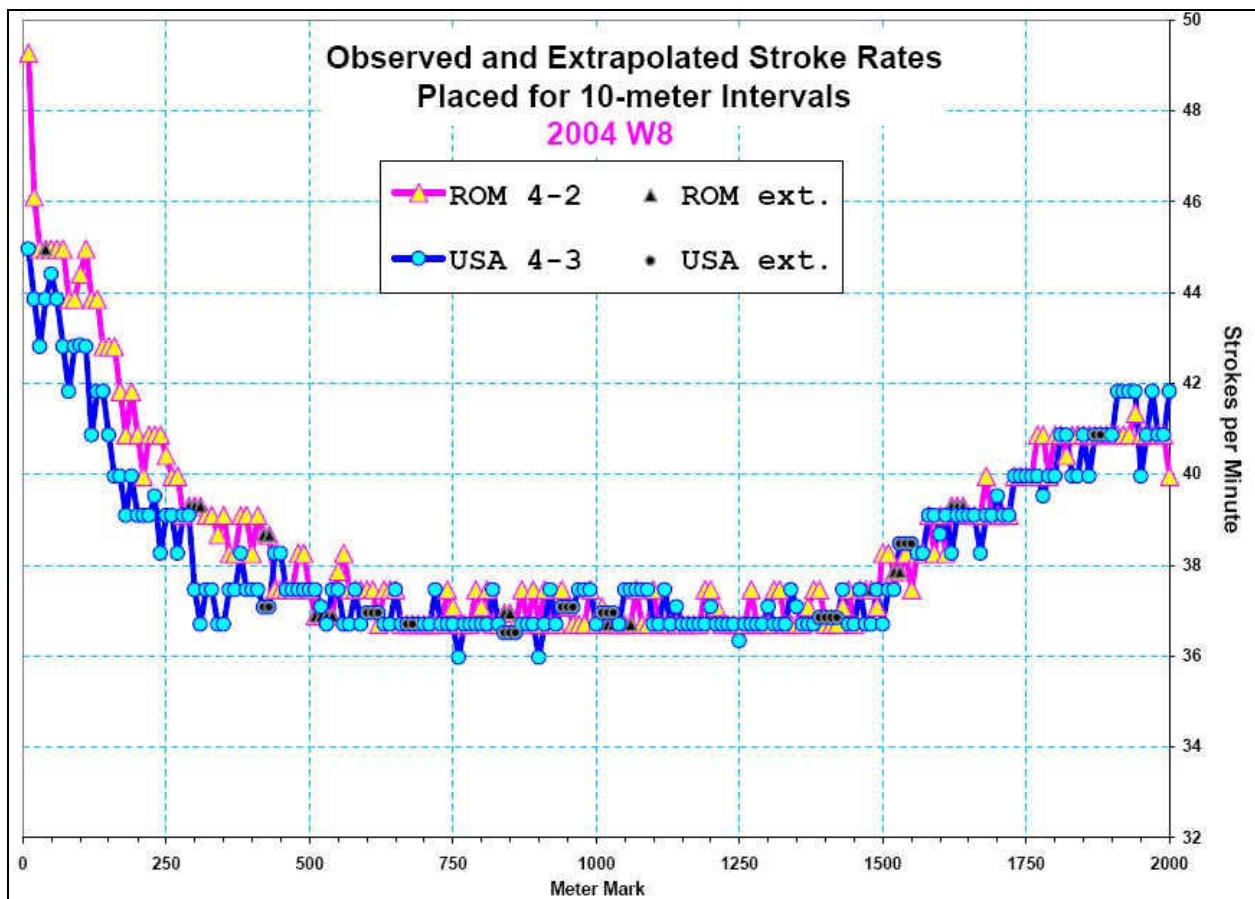


Figure 3-6: Comparison of Stroke Rate Pacing over 2000-meters

Missing stroke rate data can be accurately extrapolated when blind spots are for short durations (10-15 strokes or less). Gaps of longer duration are impossible to extrapolate with certainty. The extrapolation of missing stroke rates involves estimating the number of catches not observed. For longer blind spots, adding or subtracting an extra stroke to this missing strokes estimate could still lead to reasonable stroke rates. The Race Observation Event Log makes an initial extrapolation estimate based on the stroke rate pacing immediately prior to the blind spot. However, the race analyst can use subjective judgment to manually override this estimate if it appears unreasonable after examining the graphical pattern of stroke rates recorded.

Generic Drive Model of a Position Duel

Limiting consideration to a single duel between two crews in a race, a drive model is proposed as a generic sequence of drive segments. For any given duel, the generic drive model (see Figure 5-1) can be used to identify some or all of the following drive segments:

Spotting Segment: This starts at the beginning of the race and continues until the point (**W**) where the maximum lead is gained by the challenger crew. The eventual winning crew “spotted” the challenger a lead that would eventually be overcome.

Closing Segment: This starts at the point at which the challenger is spotted its maximum lead (**W**) and continues until the final passing point (**P**) in the duel at which the eventual winner passes the loser never to relinquish the lead again.

Passing Segment: This starts at the final passing point (**P**) and continues until an acceleration point is reached that is subjectively interpreted to be a “holding point” (**H**) at which the psychology of the race may have changed.

Holding Segment: This starts at a holding point (**H**) and continues until the best margin (**B**) is gained by the winning crew after reaching the passing point (**P**).

Challenge Segment: This starts at the best margin point (**B**). It continues while the challenger crew performs its come-from-behind challenge until some point (**C**) where it seems to have reached an acceleration point and changed the rate of its challenge (for better or worse).

Finishing Segment: The final segment of the race follows the challenge point (**C**) where the pacing of the race is interpreted to have changed, perhaps because the duel is effectively over.

Generic Drive Model of a Duel: “Come-From-Behind” Race with a Challenge

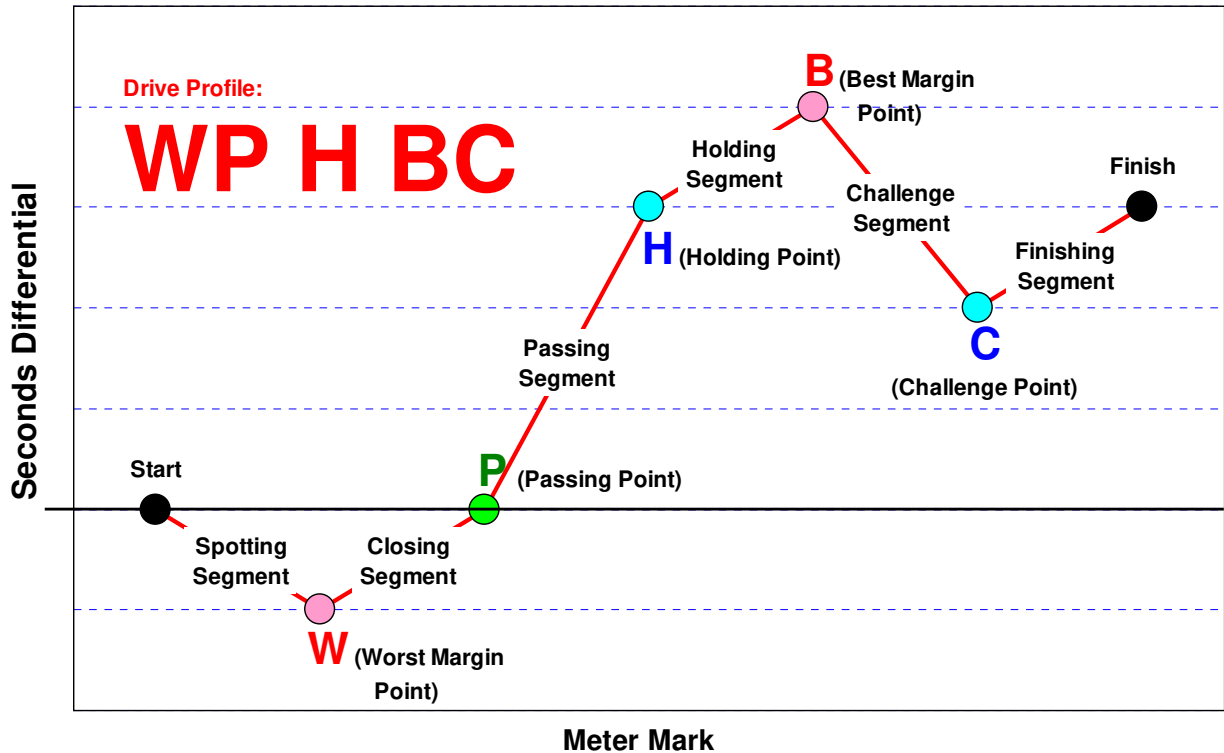


Figure 5-7: Generic Drive Model of a Position Duel

Figure 5-7 illustrates the full generic drive model of a duel. Races may not contain all of the points and segments defined in Figure 5-7. See Appendix D for several common variations on this generic model.

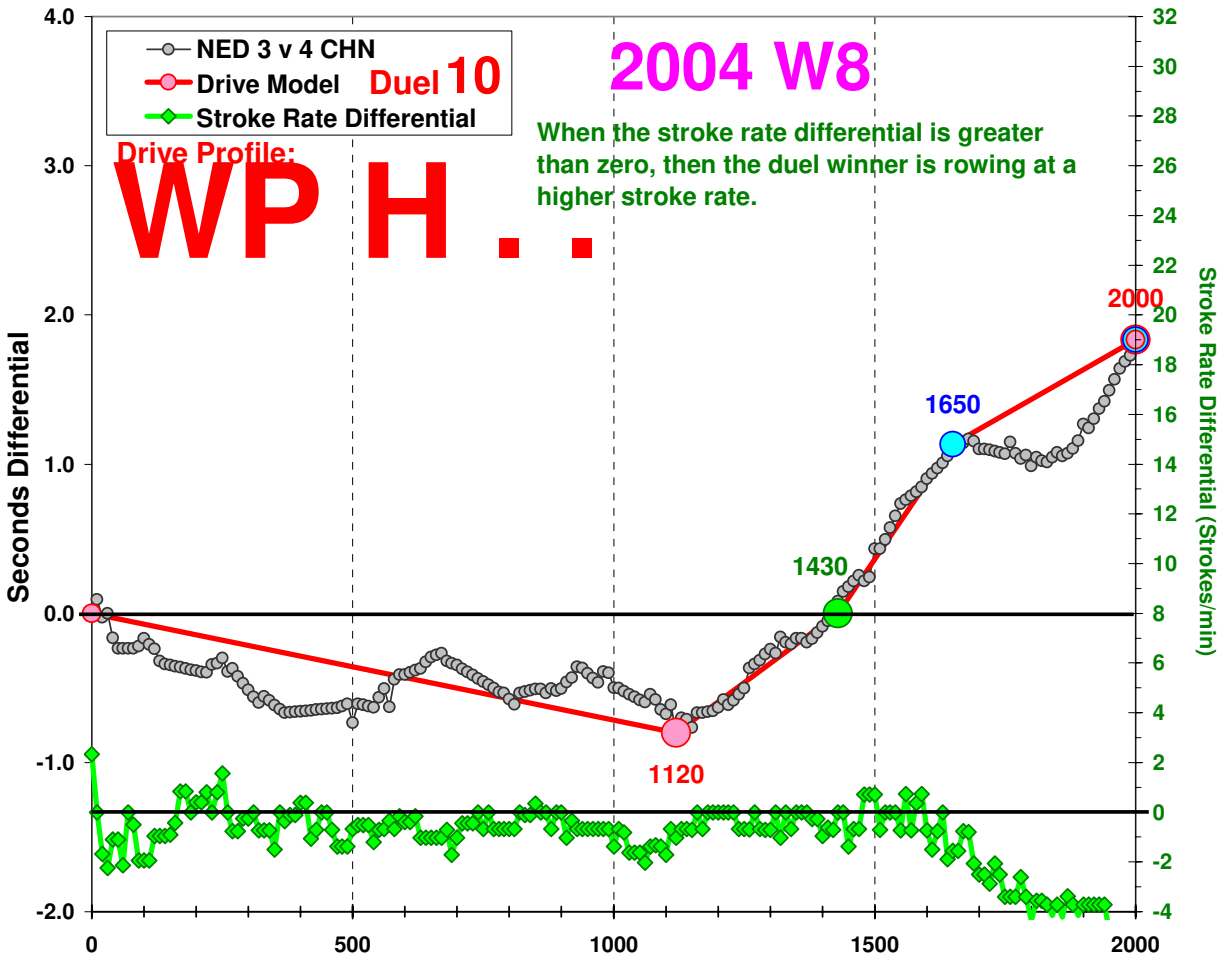


Figure 5-8: Drive Model Applied to a Position Duel

The generic drive model can be used to illustrate the components of an actual crew race duel as illustrated in Figure 5-8. In this example, the eventual third place Dutch crew comes from behind starting at 1120 meters to pass the eventual fourth place Chinese crew at 1430 meters. A “holding point” is observed at 1650 meters after which Netherlands sits on just over a one-second lead until the last 125 meters where it builds its lead to almost two seconds. Judging from the stroke rate differentials illustrated on this graph, 1650 meters is also the point at which

China begins to over stroke the Dutch crew by roughly 4 strokes per minute. Although China sprints at a higher stroke rate, their sprint appears to lose its effectiveness in the last 150 meters.

There are three points (**WPH**) from the generic drive model observable in this duel. The best margin for the Dutch crew occurs at the finish line, so there is no challenge segment defined after this point. If they exist in a race duel, the worst (**W**), best (**B**), and passing (**P**) points can all be analytically computed for a given race. The holding (**H**) and challenge (**C**) points are subjectively identified by the race analyst based on interpreting acceleration points before and after the best point in the duel. Therefore, races can be categorized according to combinations of the letters from the generic drive model. The “**WPH**” pattern is a classic come-from-behind race without a late race challenge. The “**HBC**” pattern is a classic holding race where the lead crew in the duel never trails their opponent.

Once all of the drive segments in a race have been identified, each of these drive segments can be analyzed in terms of their starting and ending points on the course, the marginal gaps at these points (measured in seconds), the rates at which gaps are changing (seconds gained or lost per meter traveled), and the stroke rate differentials between the crews (strokes per minute). Appendix C summarizes many of the drive parameters that can be algebraically computed for the various drive segments. These and other drive parameters can provide a rich database of performance measures for quantitative research.

*Measurements and analysis are useless
if the coach and rower don't know how to use them to improve performance.*

Valery Kleshnev
(Kleshnev, 2005, p.222)

CHAPTER FOUR: FINDINGS

Detailed data was mined from the video records of five world championship races. These races were the men's, women's, and lightweight men's finals races from the 2007 World Rowing Championships, and the men's and women's finals races from the 2004 Olympic Games. All of these races were in 8's competition, meaning there were eight rowers per crew with each pulling one oar. There was also one coxswain to steer, give commands, and motivate the crew.

Each of these championship finals contained six competing crews with the customary gold, silver and bronze medals awarded to the top three finishers of each race. Competing in the finals, all of these crews were motivated to do their best and save nothing for their next race.

This chapter graphically displays the raw results of the five case study races. The position duels for gold and silver medals are discussed. The results of these five races are illustrated using five graphs:

1. **Race Progress in Terms of Seconds behind the Leader:** This type of graph (see Figure 4-1) plots how many seconds each crew is trailing the leader – as a function of each crew's location down the 2000 meter course. Approximately 3.2 seconds equals 1 shell-length (but this varies depending on the shell and crew velocity). The legend on this graph displays the Kleshnev-style (Kleshnev, 2001(1)) pattern of which splits each crew rowed the fastest and the slowest relative to the average speed of the other 5 crews.
2. **Stroke Rates of Each Crew down the Course:** This type of graph (see Figure 4-2) plots the pacing of crews (stroke rate per minute) – as a function of each crew's location down the 2000 meter course. Black symbols on the graph show where the

stroke rate was not directly observable, but which could be algebraically extrapolated from other direct physical race observations.

3. **Crew Velocities down the Course:** This type of graph (see Figure 4-3) shows the calculated velocity of each crew – as a function of each crew’s location down the 2000-meter course. Some race courses including the 2004 Olympics course may not have buoys placed at regular intervals that are synchronized with the 250 and 500-meter splits. Having to estimate the exact location of buoys can cause inaccuracy and high variability in the calculated velocities around these split locations.
4. **Drive Model of the Gold Medal Position duel:** The progress of the duel for the gold medal is discussed and interpreted (see Figure 4-4).
5. **Drive Model of the Silver Medal Position duel:** The progress of the duel for the silver medal is discussed and interpreted (see Figure 4-5).

The findings in this chapter are explained in a narrative format to illustrate how to use the graphs and introduce many of the concepts researched in this dissertation. The interpretations accompanying the five case study races within this chapter illustrate the concepts of drives and duels. The narration and interpretations given are unavoidably subjective. However, the graphs themselves do the real work by presenting race findings in a visual form ready for interpretation. Later on in this dissertation, quantitative analysis is presented that objectively summarizes the overall drive patterns and calculates the probabilities of holding leads of varying lengths as a function of position along the course and whether the trailing crew in a duel is driving on the leading crew.

Case 1: 2004 Olympics Women's Eights Finals (2004 W8)

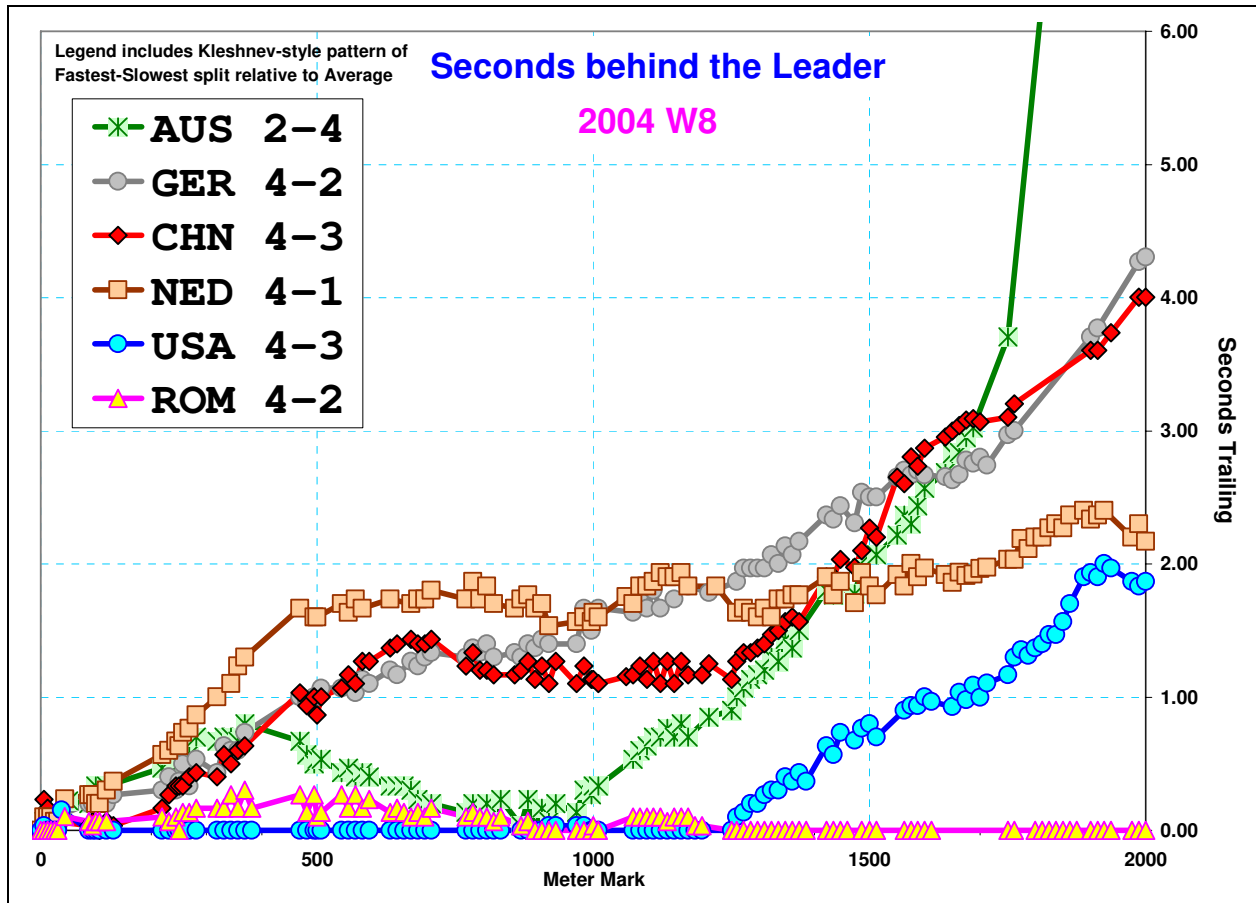


Figure 4-1: 2004 W8 Race Progress in Terms of Distance behind the Leader

USA led by a narrow margin for most of the first 1250 meters. At 1250 meters, the Romanians initiated a decisive drive and pulled steadily away from USA and the other crews. With about 100 meters to go, the Romanians appear to have eased up and coasted to the win.

Australia fell back to fifth place by the end of their racing start, after which they put on a challenge and almost took the lead shortly before the 1000-meter mark. In the last 1000 meters, Australia faded quickly and appears to have completely collapsed somewhere within their blind spot over the last 250 meters – perhaps associated with a crab, injury, or equipment malfunction.

The crew from the Netherlands spotted everyone else a lead in the first 500-meters, after which their race appears to have completely changed – rowing through three other crews and almost catching the USA in the last 100 meters.

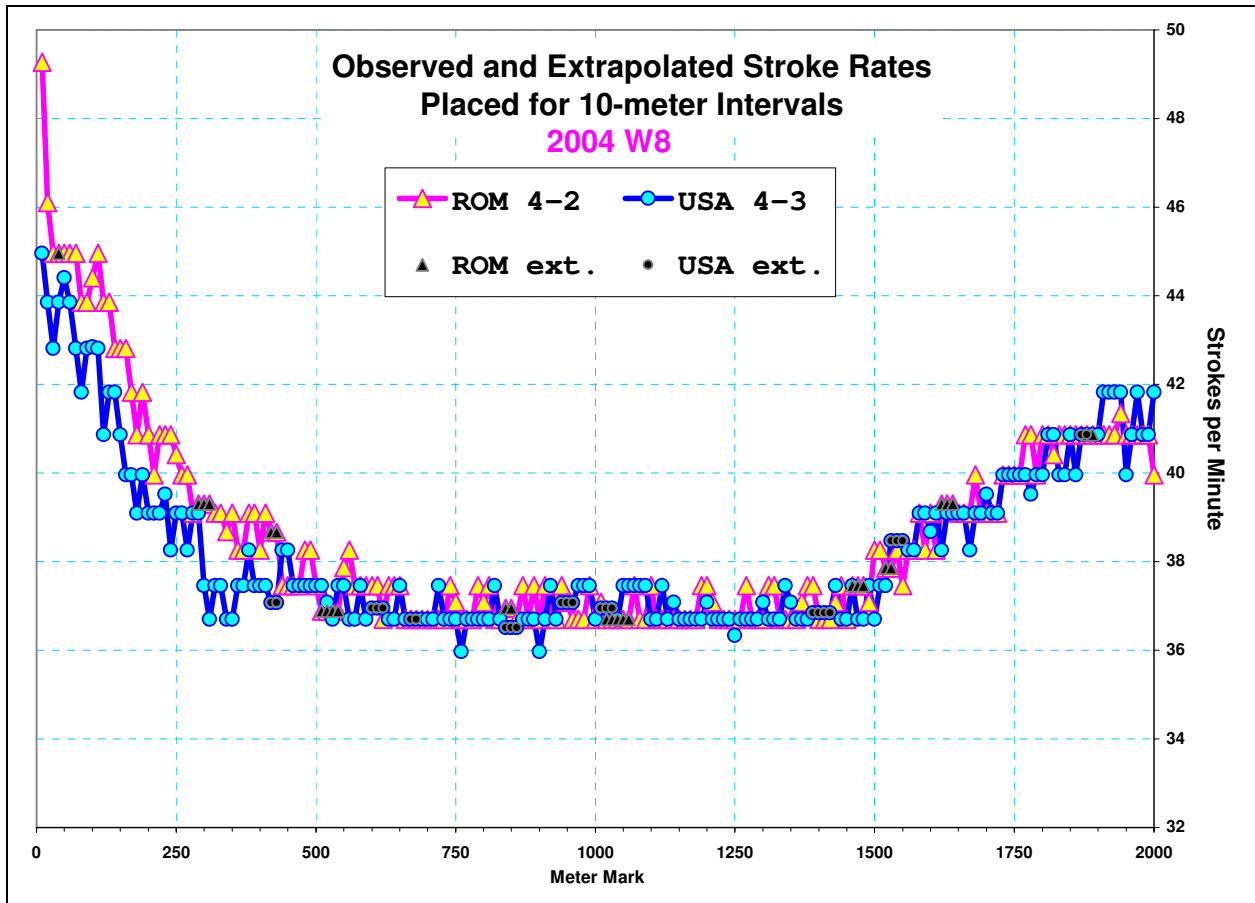


Figure 4-2: 2004 W8 Stroke Rates of Each Crew down the Course

The USA under-stroked the Romanian team during the racing start and for the first 600 meters. After that, these crews rowed nearly stroke-for-stroke identical pacing including a steadily accelerating sprint in the final 500-meters. Comparing the relative stroke rates to the relative positioning of these crews, the difference in performance between these crews cannot be attributed to a difference in stroke rate strategy. The fact that Romania over-stroked USA in the first 500 meters also suggests that USA did not burn itself out early in the race simply due to a higher stroke rate pacing strategy (although they may have exhausted themselves in other ways).

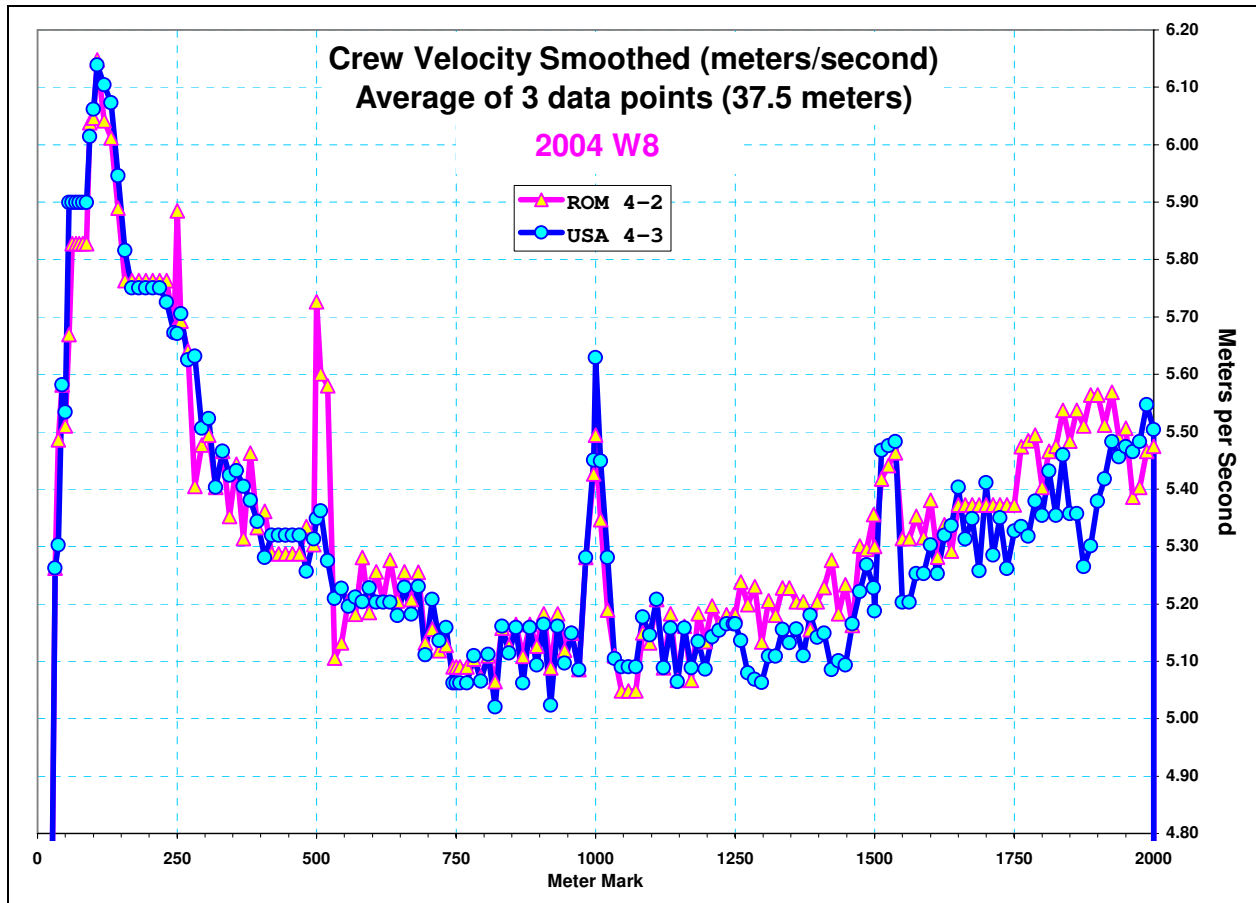


Figure 4-3: 2004 W8 Crew Velocities down the Course

The USA and Romania matched each other closely in velocities early in the race. For most of the last 850 meters, Romania moved faster than the USA (until about 100 meters to go).

Note that the wide fluctuations in velocity around the 500-meter splits are due to two factors. First, buoy locations were not evenly spaced in synchronization with the 500-meter markers. Using estimated buoy locations can result in inaccuracies in velocity calculations. Second, buoy spacing immediately before and after the 500-meter markers averaged around 6.25 meters rather than the 12.5-meter spacing between other buoys. This naturally leads to wide divergence in actual velocities between buoys. Narrow buoy spacing captures much less than

one full stroke, and shell velocity varies considerably within each stroke. Therefore, the wide ranging velocities graphed might precisely illustrate the wide range in actual velocities over buoy spacing distances that are much less than one full stroke length.

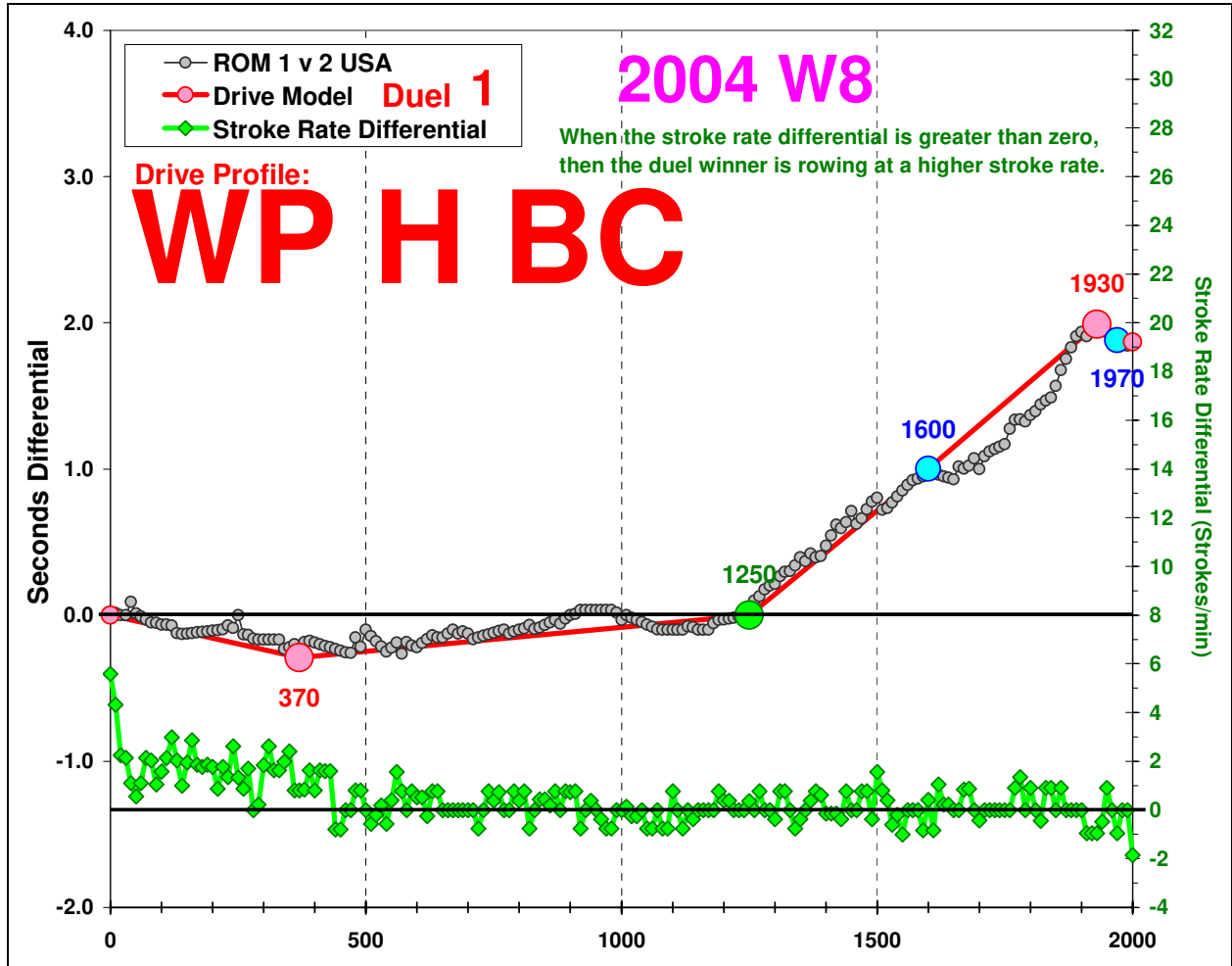


Figure 4-4: 2004 W8 Drive Model of the Gold Medal Position duel

The gold medal position duel illustrates the complete WPHBC generic drive pattern. The Romanians spot the USA a lead over the first 370 meters in spite of overstroking the USA. They keep within close striking range until 1250 meters when they finally catch the USA, after which they steadily pull into the lead. At around 1600 meters, Romania reaches a hold point where they appear tempted to just sit on a lead of just over 1 second. The last 100 meters shows the

pattern of a challenge drive – but way too late to be effective. This appears to be a fade by Romania as their stroke rate also eased up, falling slightly below USA as the finish line neared.

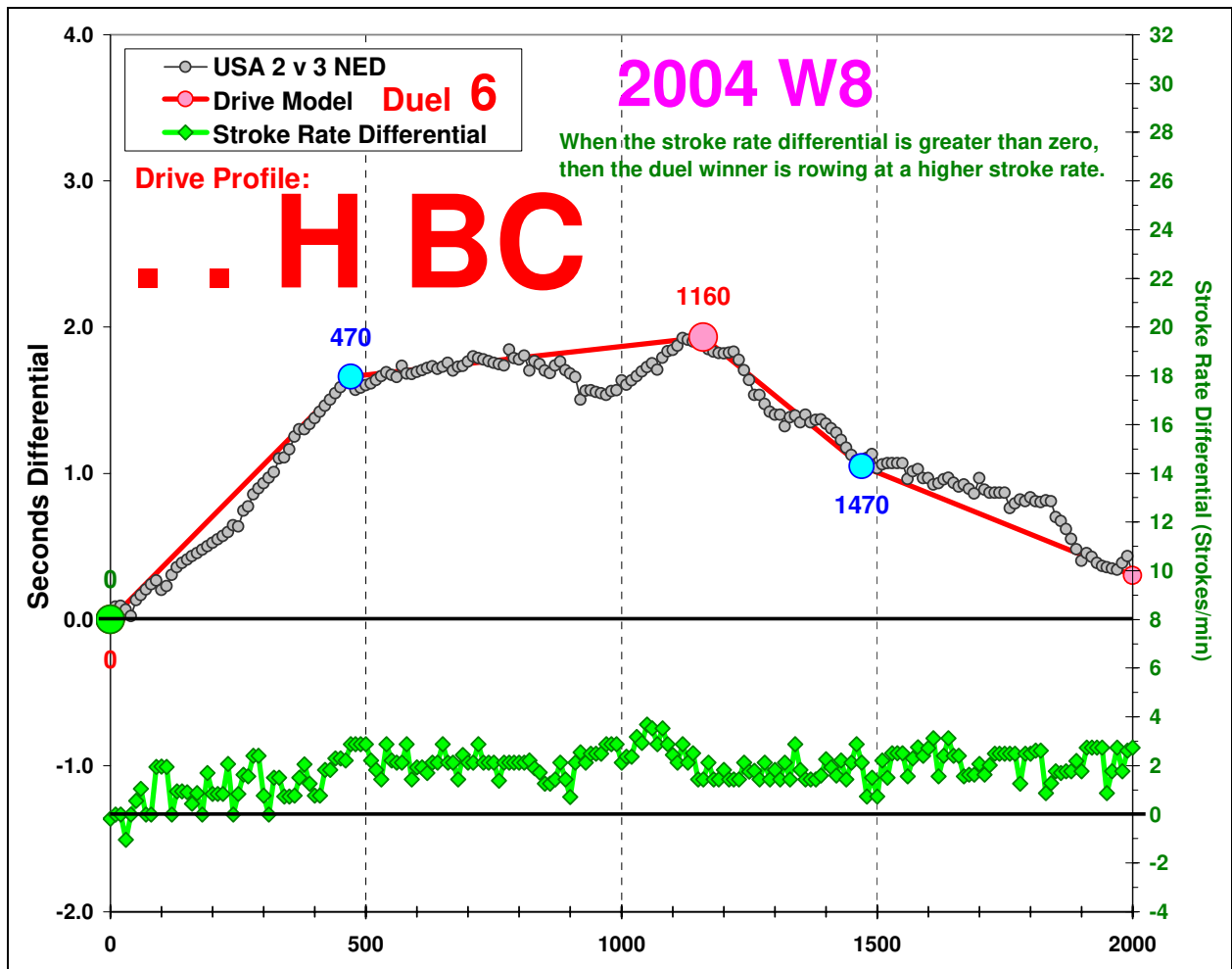


Figure 4-5: 2004 W8 Drive Model of the Silver Medal Position duel

The position duel for the silver medal follows the classic HBC hold race pattern. USA builds a lead of about 1.8 seconds before reaching a holding point at 470 meters. They sit on this lead and eventually extend it to roughly 2 seconds by 1160 meters. The Netherlands then puts on a challenge drive. The rate of gain slows as crews begin their sprints with about 500 meters to go. The USA crew may have given up on trying to catch the Romanians near the end of the race, but they rowed just hard enough to hold on to a narrow lead for the silver medal over Netherlands.

Case 2: 2007 World Championship Women's Eights Finals (2007 W8)

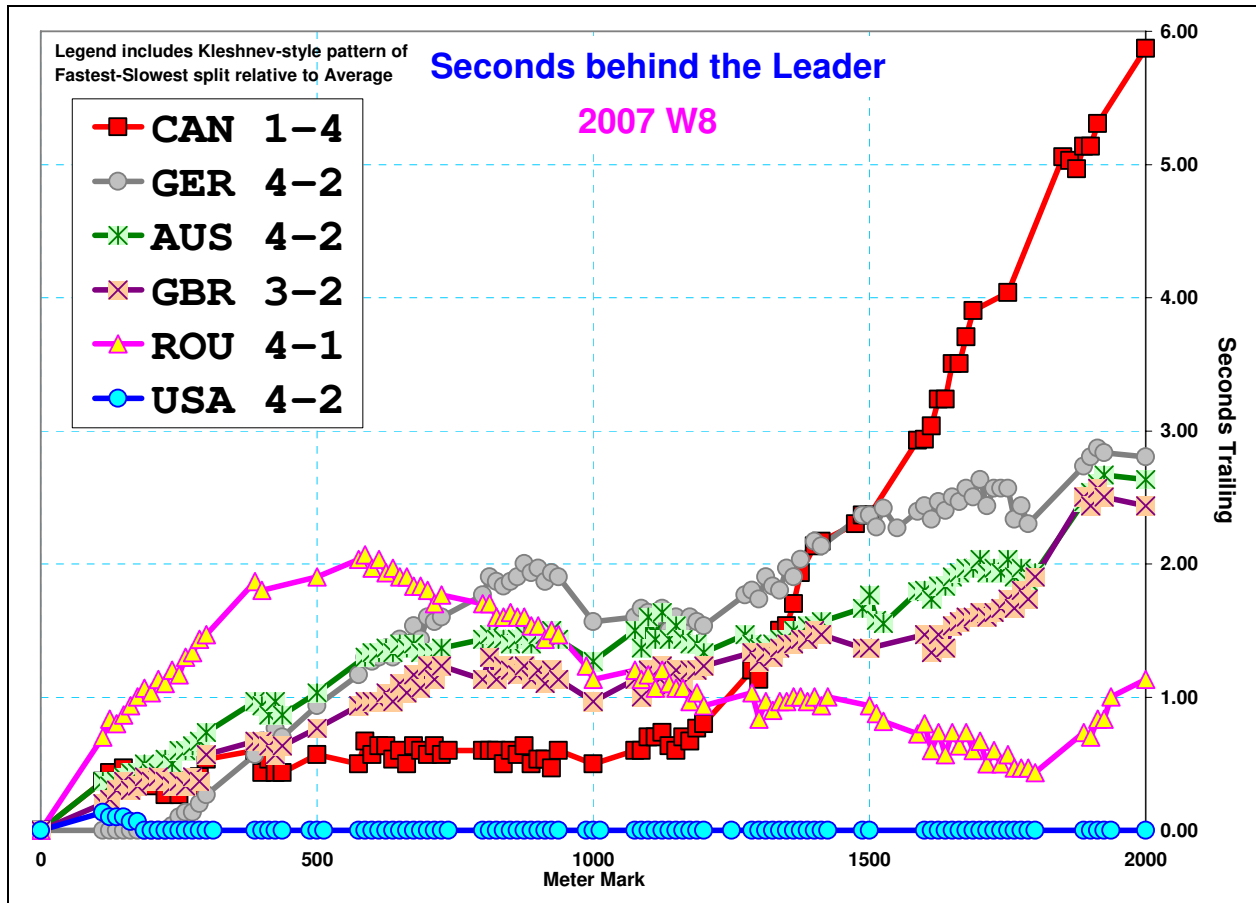


Figure 4-6: 2007 W8 Race Progress in Terms of Distance behind the Leader

After falling marginally behind during the racing start, USA takes the lead at about 200 meters and holds this lead for the rest of the race. The Romanians spot all of their opponents an early lead – falling decisively behind the USA by a full 2 seconds by 600 meters. The Romanians then put on a sustained drive for most of the rest of the race. They row through four other crews, but cannot quite catch the USA with 200 meters to go. With 200 to go, the USA responds to the Romanian challenge and sprints ahead to win by just over 1 second. Canada keeps the race for gold close for about 1200 meters, after which the crew fades rapidly. All the other crews row through Canada who finishes in last place by a wide margin.

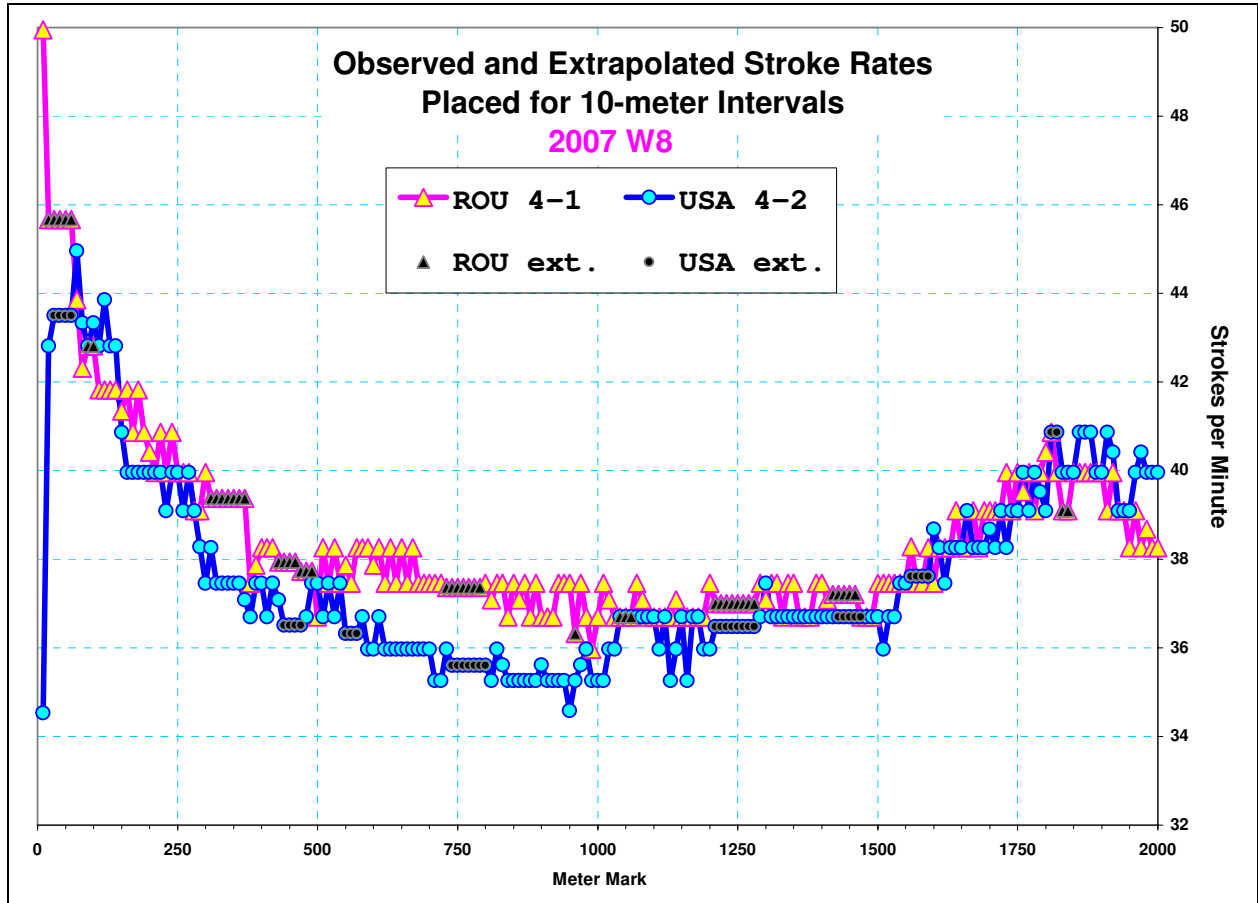


Figure 4-7: 2007 W8 Stroke Rates of Each Crew down the Course

In the duel for gold, Romania and USA match stroke rates closely over much of the course. During the second 500 meters, Romania overstakes the USA. This stroke rate increase for Romania coincides with the first half of Romania's long challenge drive on the USA. In the last 100 meters, the Romanian crew appears to be broken. The USA is building their lead while the stroke rate for Romania is fading.

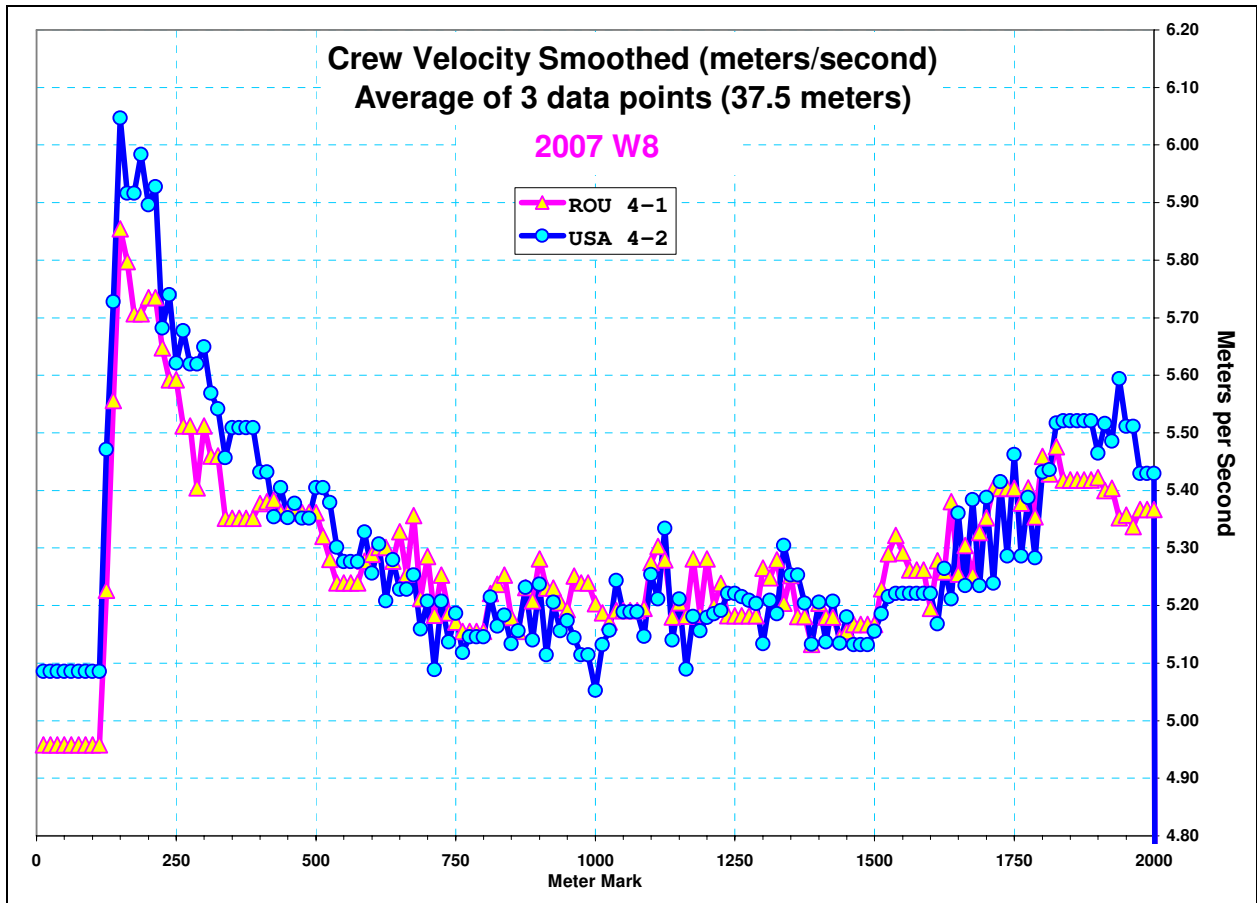


Figure 4-8: 2007 W8 Crew Velocities down the Course

USA maintains a higher velocity over Romania for the first 700 meters. Romania's long challenge drive is illustrated by slightly higher velocities throughout the middle of the race. The USA is noticeably faster over the last 200 meters.

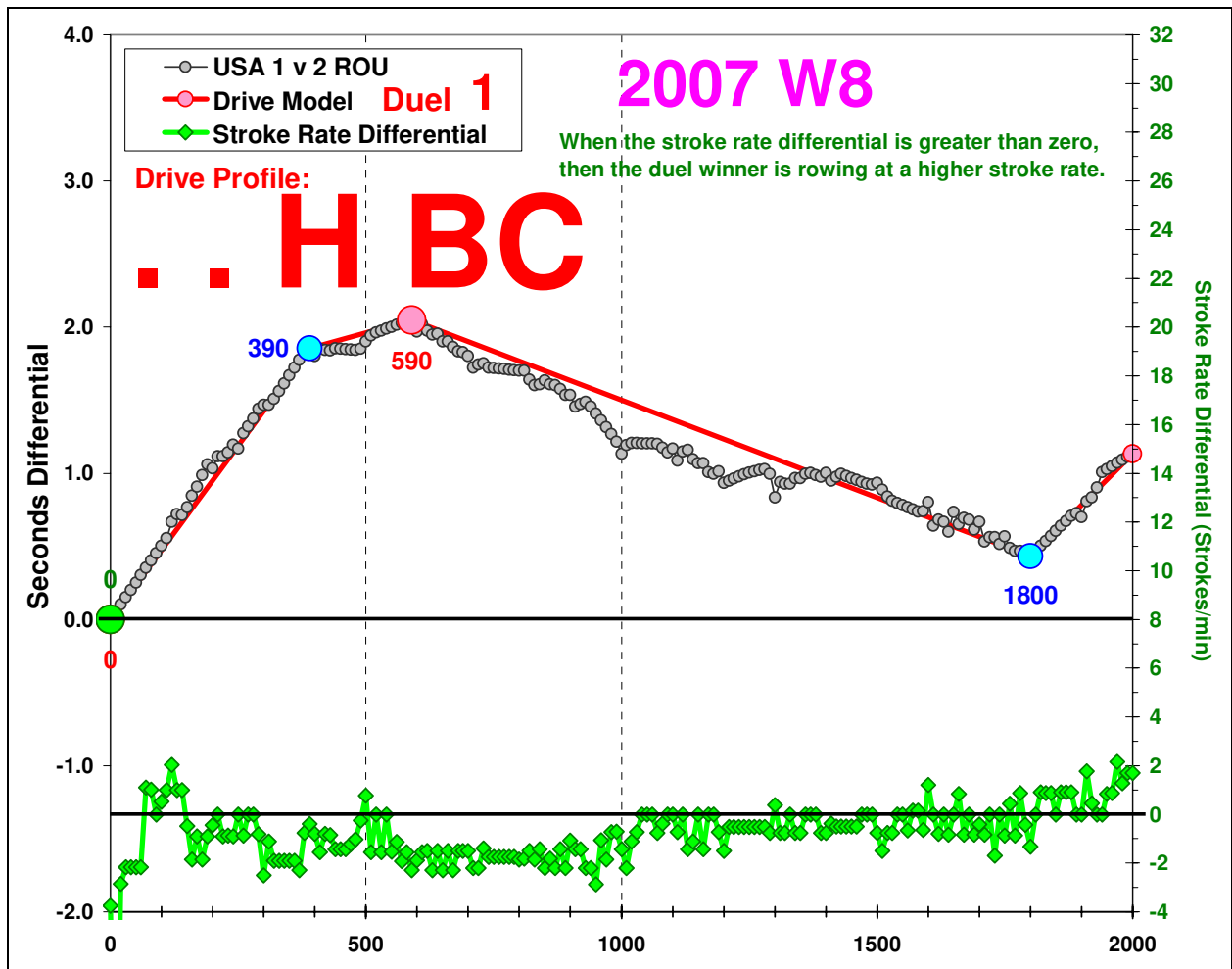


Figure 4-9: 2007 W8 Drive Model of the Gold Medal Position duel

USA follows a classic HBC holding race strategy. A holding point is reached at 390 meters. The best lead by USA is at 590 meters, after which Romania displays a long and steady challenge drive. At 1800 meters, USA reaches a clear challenge point, after which it accelerates and builds back a more comfortable lead. For most of the first half of the race, Romania overstrokes USA, yet trails the USA. The USA's final drive is associated with a higher stroke rate differential.

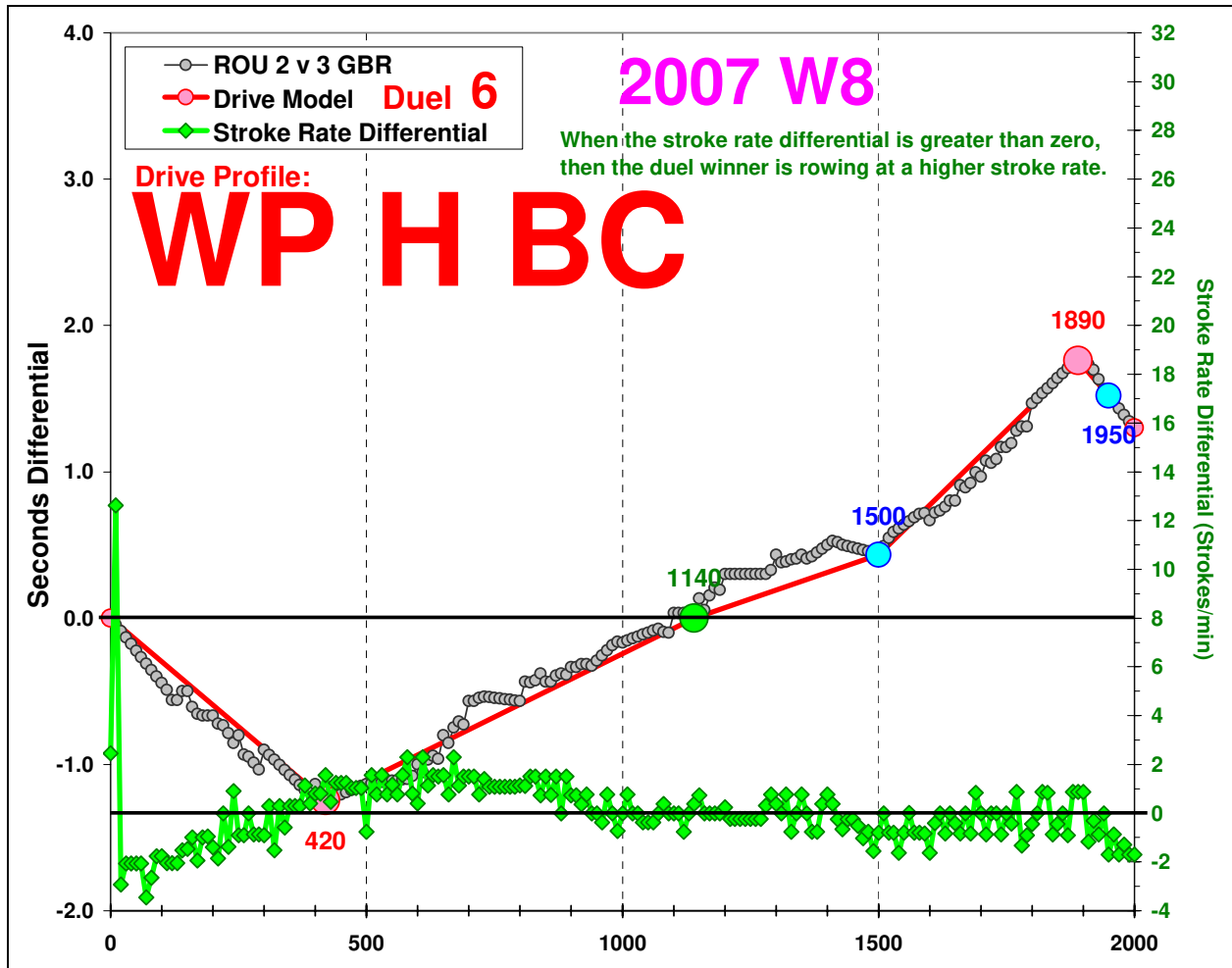


Figure 4-10: 2007 W8 Drive Model of the Silver Medal Position duel

The silver medal duel follows the classic come-from-behind race strategy. Against USA, Romania's come-from-behind drive fell short. Against Great Britain, the strategy works well. Romania understroked and spotted Great Britain a lead of over 1-second by the 420-meter point. This lead proved not to be decisive as Romania drove steadily through Great Britain for most of the rest of the race. The 1500 meter mark is viewed as a hold point, after which Romania accelerates its rate of gain. At 1890 meters, Romania is fading fast to USA and also starts to fade to Great Britain, but the nearly 2-second lead proves easy to hold this late in the race.

Case 3: 2007 World Championship Lightweight Men's 8's Finals (2007 LM8)

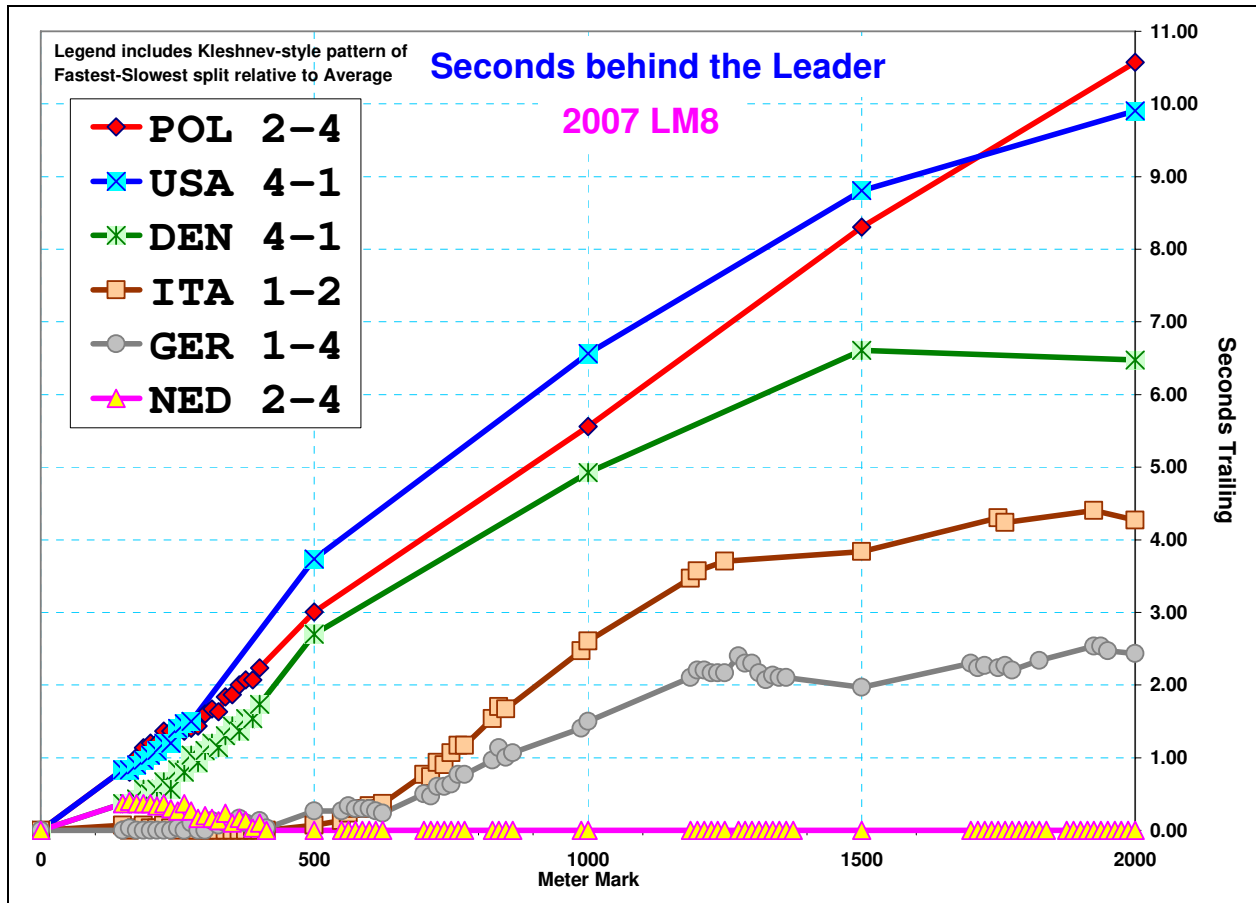


Figure 4-11: 2007 LM8 Race Progress in Terms of Distance behind the Leader

Germany and Italy battle very closely for the lead over the first 400 meters. The Netherlands is close behind in third place. By 600 meters, Netherlands takes over first place. They build this lead until 1250 meters at which point they comfortably sit on over a 2-second lead for the remainder of the race. As Netherlands drives into a comfortable lead for the gold, Germany is driving ahead of Italy to build a comfortable 2-second lead for the silver medal. The duels for gold and silver seem to parallel each other.

Denmark puts on a drive in the last 500 meters to extend their lead over the fifth and sixth place crews, but is too far behind to threaten for a medal.

The best position duel of the day may have been between USA and Poland for fifth place. The duel was close all the way with USA putting on a decisive drive somewhere in the last 500 meters (unfortunately during a long blind spot while both non-medal crews were out of camera view).

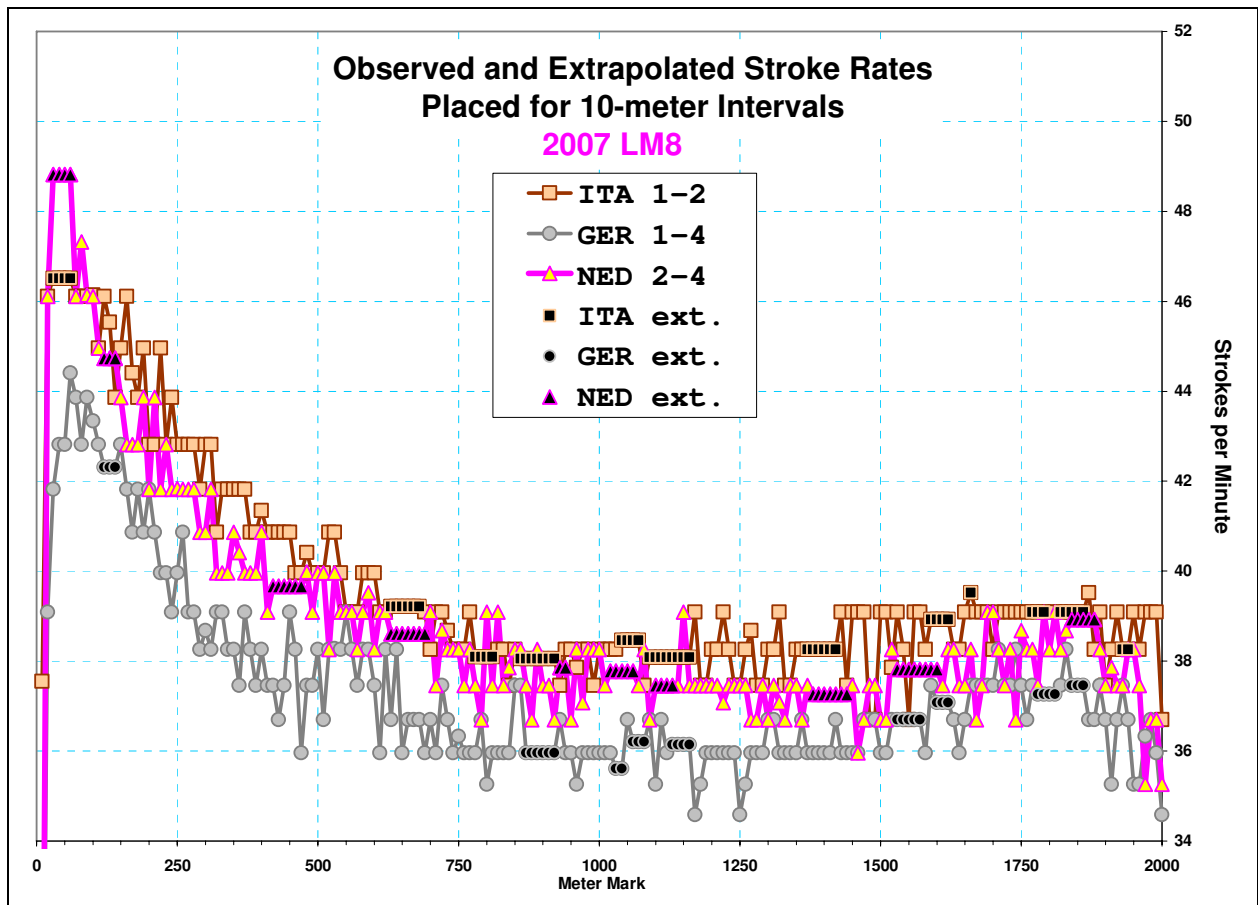


Figure 4-12: 2007 LM8 Stroke Rates of Each Crew down the Course

Silver medalist Germany understroked the other medalists the entire race. Bronze medalist Italy overstroked the other medalists the entire race. Gold medalist Netherlands seems to have gotten it just right while maintaining a middle pacing most of the way. Netherlands did start very high (over 48 strokes per minute) but still spotted the other contenders a small lead. In the last 50 meters with a comfortable lead for the gold, Netherlands stroke rate faded slightly.

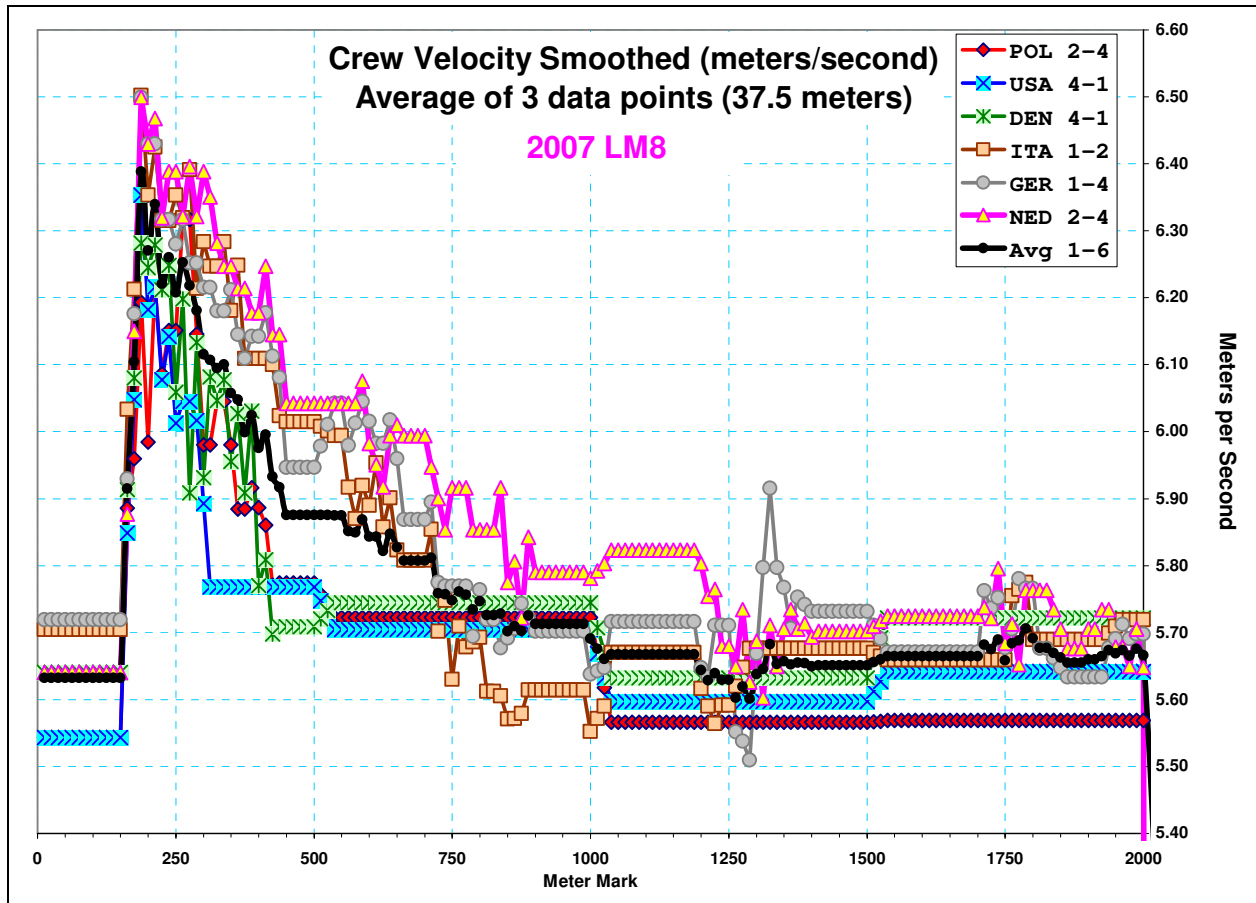


Figure 4-13: 2007 LM8 Crew Velocities down the Course

For the middle 500 meters, the relative velocities of the three medalist crews is consistent with the drives these crews put on each other in order to sort out the medals positions. Germany showed greater speed than anyone else between 1300 and 1500 meters, but the Dutch lead was already decisive. Italy was the slowest of any crew between 750 and 1000 meters – allowing Germany to drive to a decisive silver medal lead. It is possible that Italy burned itself out in the first 750 meters with its higher stroke rate and temporary battle for the lead. The medals races seem to have been decided by halfway through the race with the last three crews never in contention for a medal.

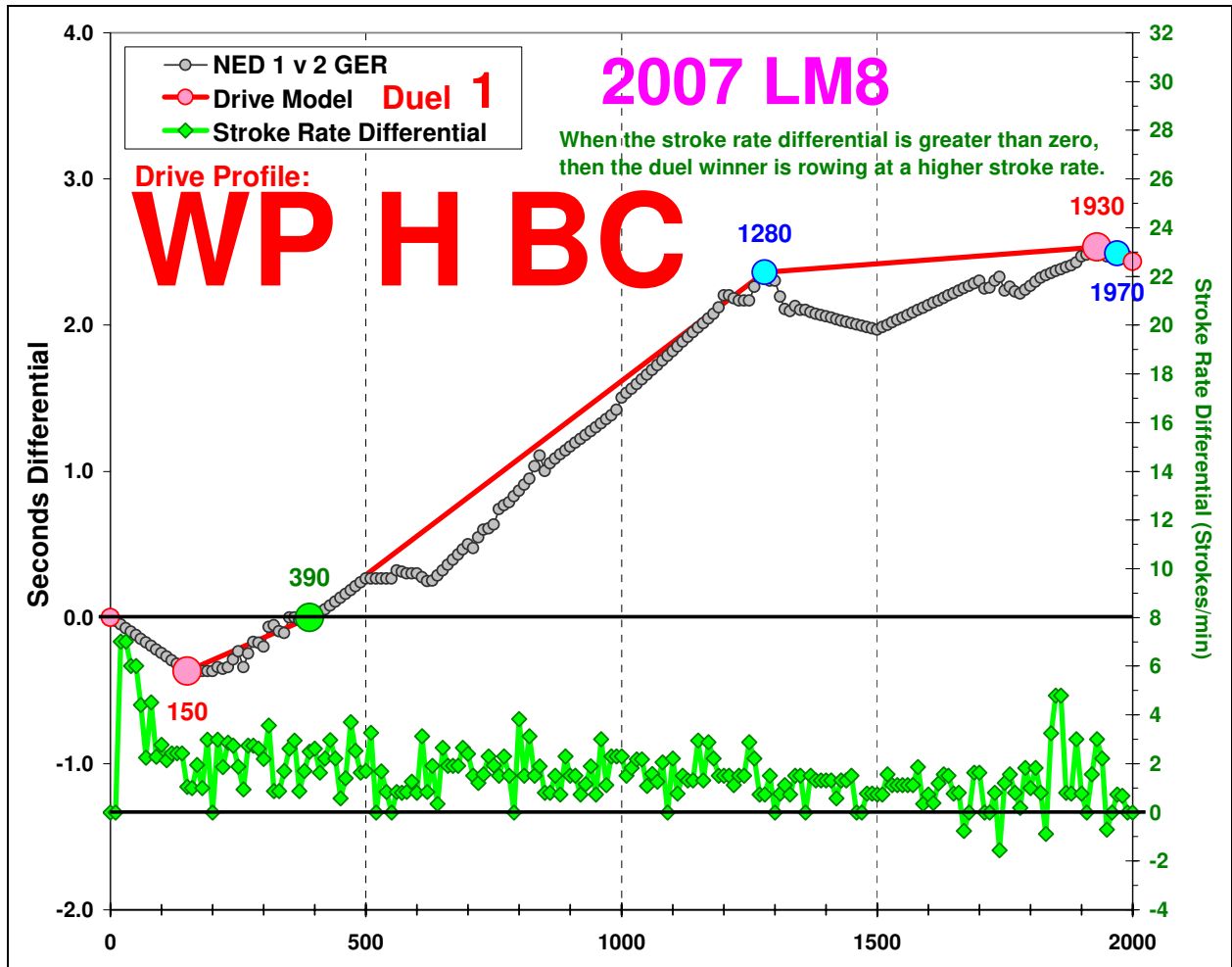


Figure 4-14: 2007 LM8 Drive Model of the Gold Medal Position duel

In the gold medal duel, Netherlands spotted Germany a small lead during the racing start. By 390 meters, Netherlands took the lead over Germany. Afterwards, they drove steadily toward a decisive lead of 2.5 seconds by 1280 meters. Germany then put on a challenge drive that lasted until the 1500-meter mark. Netherlands out-sprinted Germany over the last 500 meters to gain its best lead with less than 100 meters to go. Netherlands overstroked Germany the entire race, but with the stroke rate differential gradually narrowing throughout the entire race.

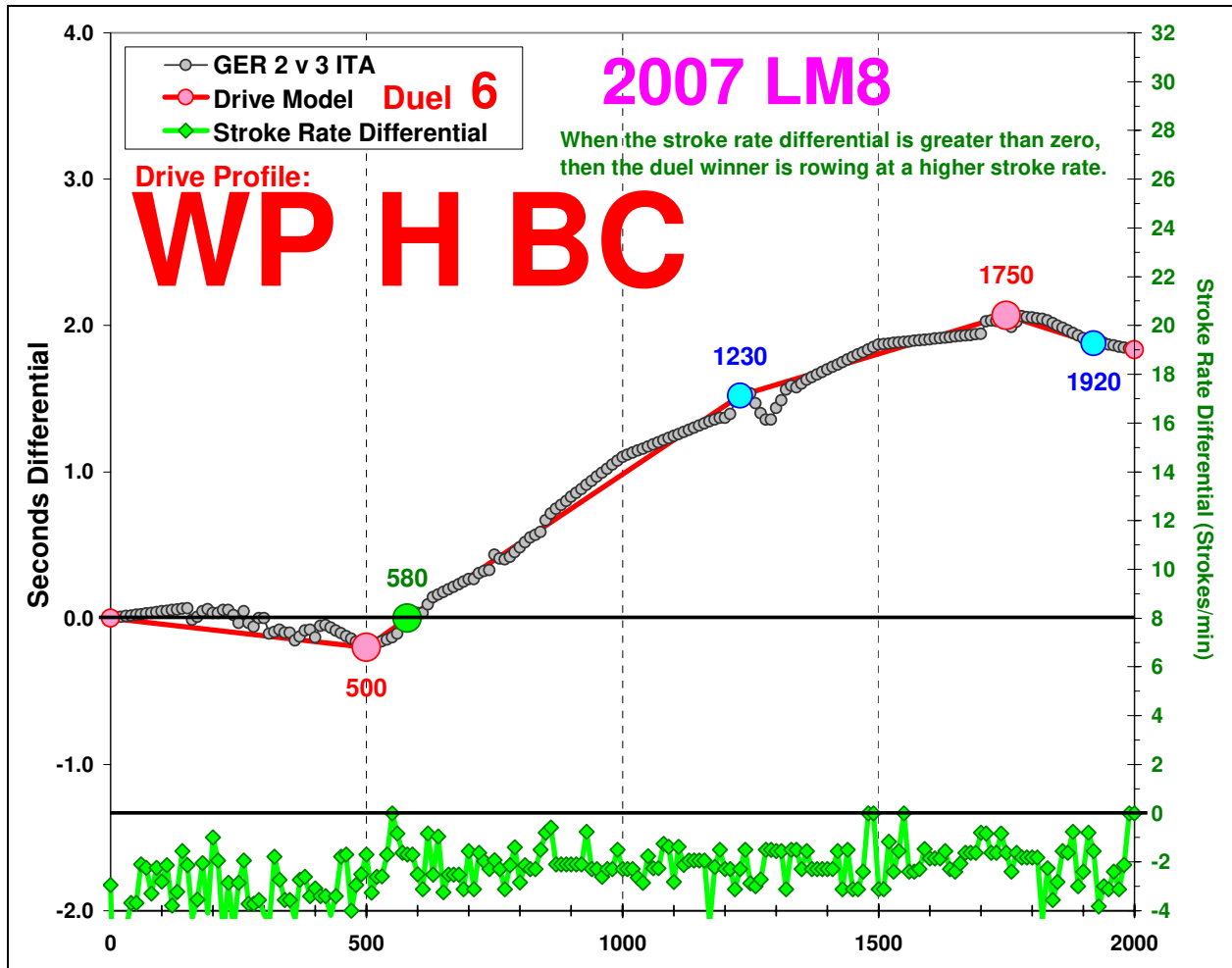


Figure 4-15: 2007 LM8 Drive Model of the Silver Medal Position duel

The silver medal duel was like the gold medal duel in terms of following the generic WPHBC drive pattern. Germany understroked Italy the entire race. The Italian stroke rate differential was greatest in the first 500 meters during which they drove to a small lead. Germany steadily drove on Italy from the 500 to the 1750 meter mark. The hold point for Germany at 1230 meters shows a brief dip in performance against Italy. The late Italian drive was insignificant against Germany's decisive lead by then for the silver.

Case 4: 2004 Olympics Men's Eights Finals (2004 M8)

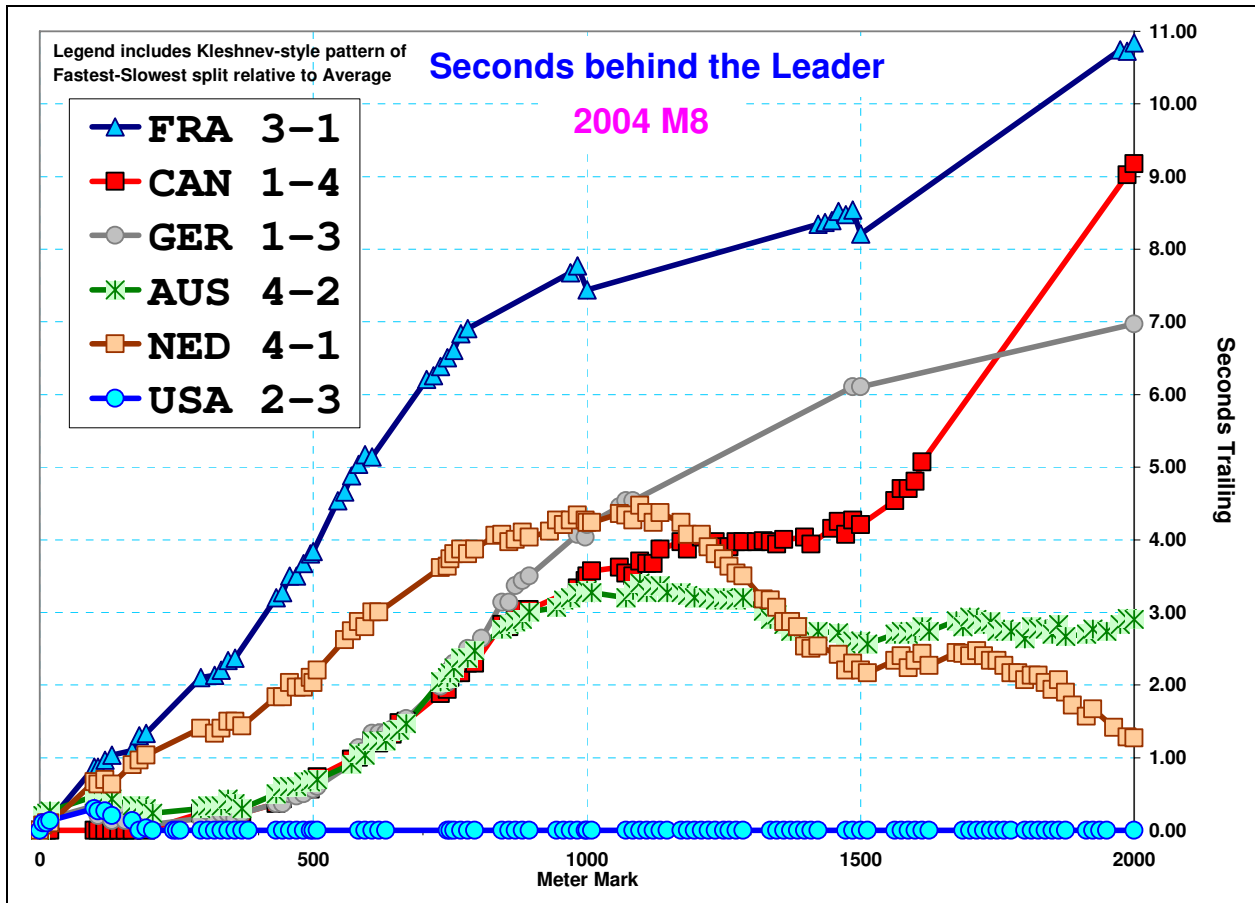


Figure 4-16: 2004 M8 Race Progress in Terms of Distance behind the Leader

The USA fell just slightly behind the Canadians in the start, but then took the lead which it held for the rest of the race. After the start, USA drove steadily to a decisive 3-second lead by the 1000-meter mark. Canada, Germany and Australian battled very closely for second place until Australia asserted itself at the midpoint of the race. Meanwhile, Netherlands in fifth place the entire first half of the race began to drive on everyone. They drove through everyone else in the last half to take the silver, but their gap of over 4 seconds to the USA at the 1000-meter point was too much to overcome. Their challenge for gold fell short by just over 1 second.

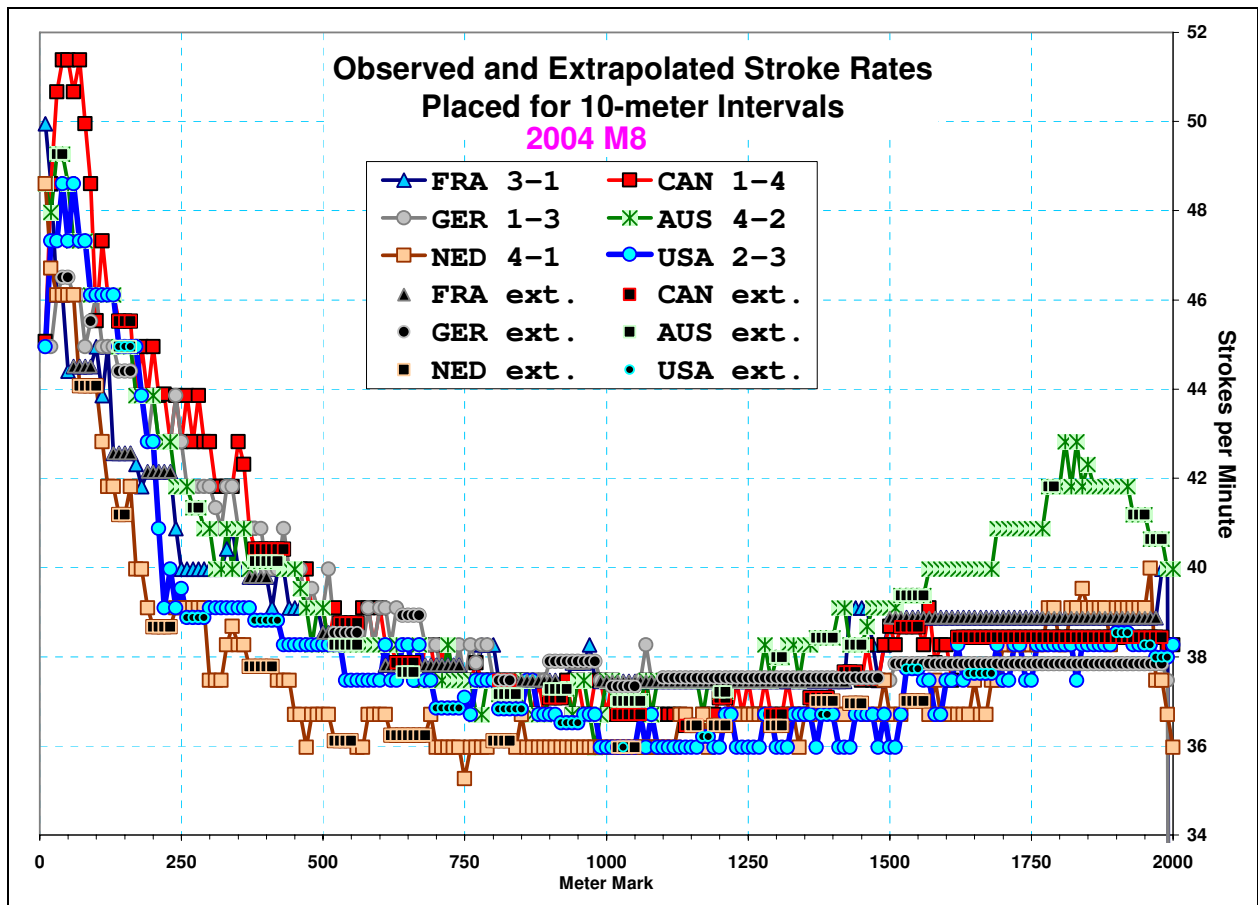


Figure 4-17: 2004 M8 Stroke Rates of Each Crew down the Course

The Netherlands race plan appears to have been to understroke its competition over the first half of the race. After rowing at 36 strokes per minute over the second 500 meters, Netherlands increased their rate to 37 strokes per minute for the third 500 meters. This coincides with when they started to drive on all of their opponents. The Australian sprint over the last 500 meters overstroked all of their opponents while reaching a peak around 42 strokes per minute. Nevertheless, Netherlands continued to build its lead over Australia in spite the fact that their final sprint was only at 39 strokes per minute – much lower than the 42 to 46 strokes per minute the Netherlands demonstrated itself capable of in their racing start. The USA in winning the

gold medal started the race as high as 48 strokes per minute, rowed the body of the race around 36 to 37 strokes per minute, but never got above 38 in the last 500 meters. The USA head coach admitted later that they never used their full sprint. The Netherlands drive for silver was impressive, but the USA lead was so decisive that they never needed to sprint and were content to just sit on their lead.

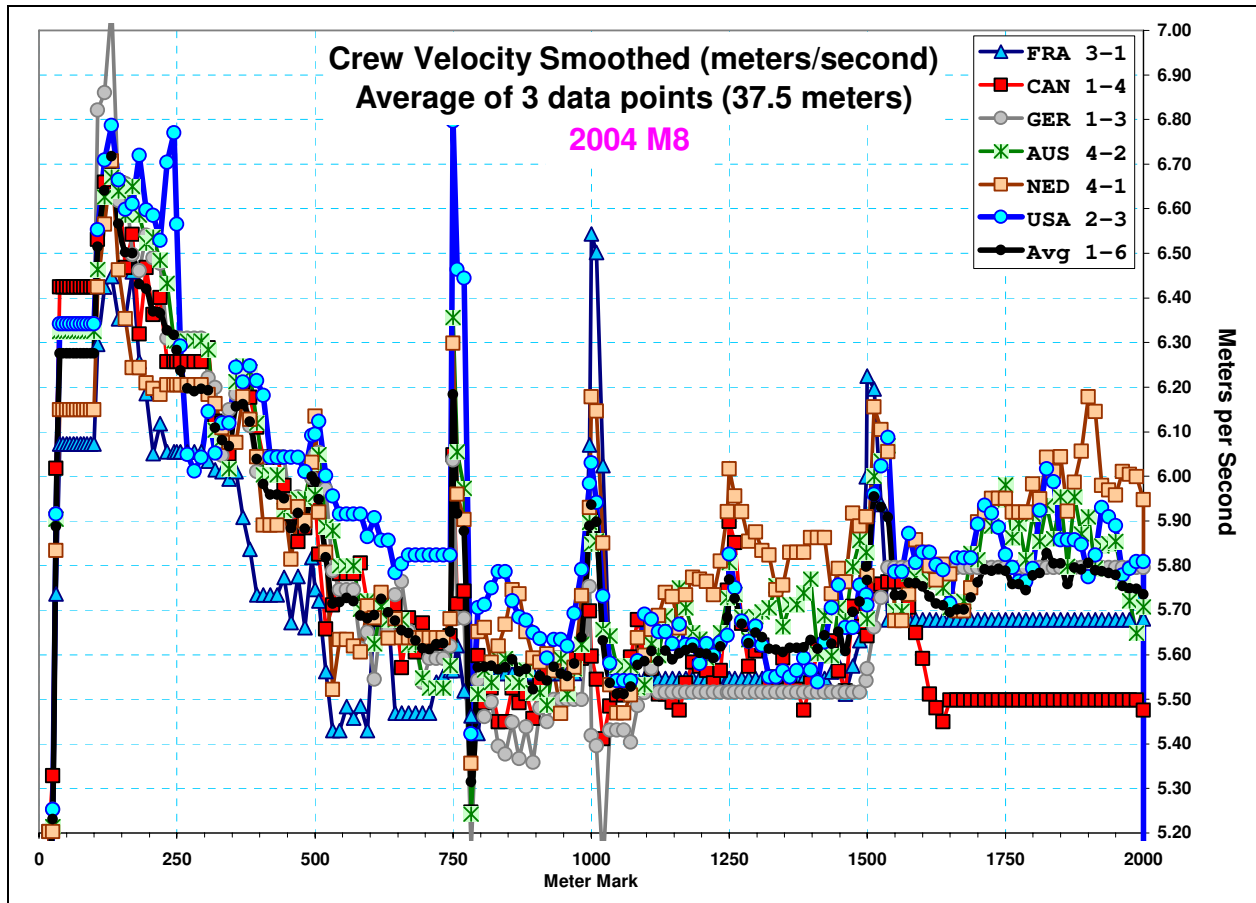


Figure 4-18: 2004 M8 Crew Velocities down the Course

USA showed superior speed over the first 1000 meters. Netherlands showed superior speed over the last 1000 meters. Canada started well, but may have finished the last 300 meters at a reduced stroke rate while in a blind spot to the camera. (Blips in velocity at the 250-meter marks are due to irregular, shortened buoy spacing.)

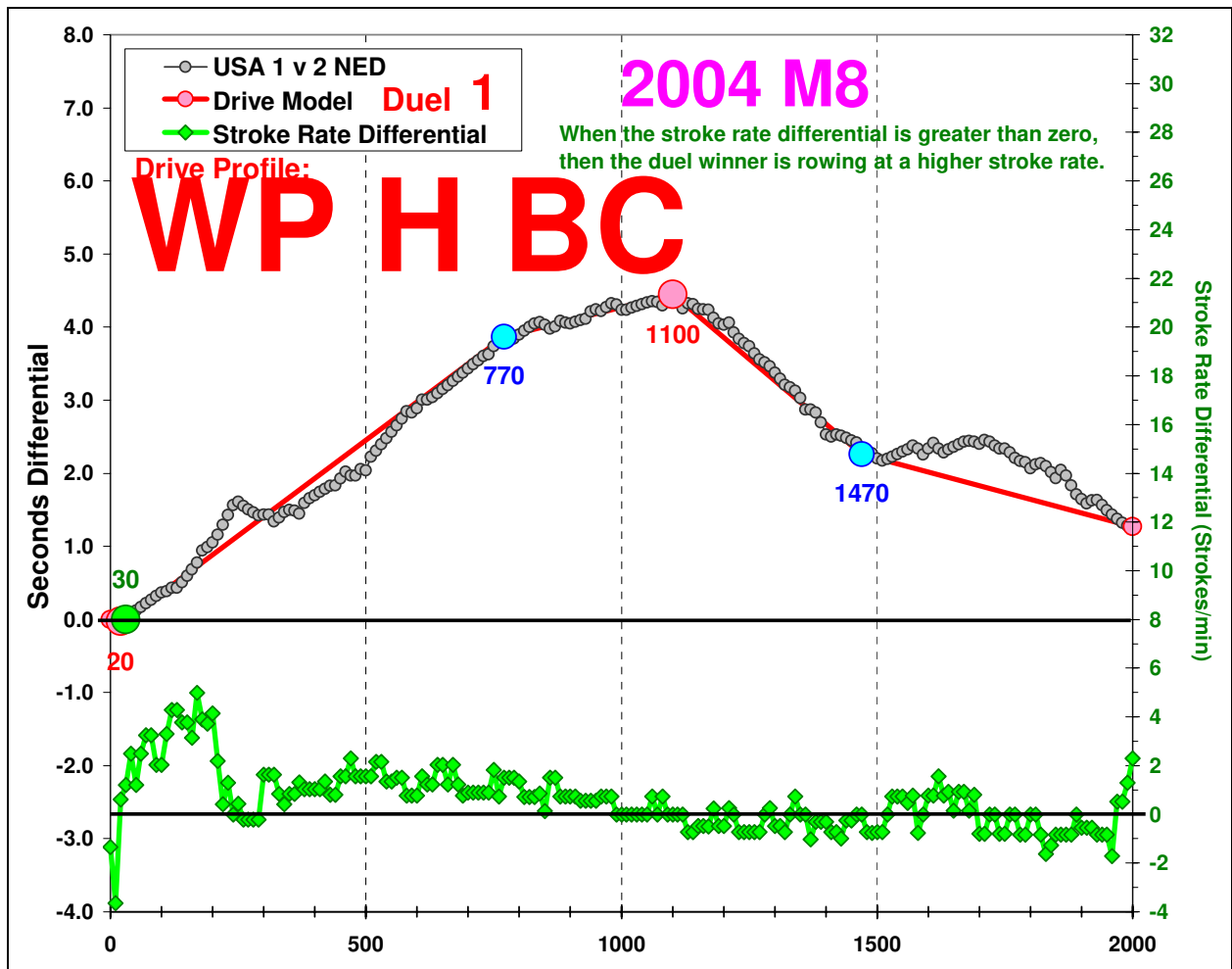


Figure 4-19: 2004 M8 Drive Model of the Gold Medal Position duel

The gold medal duel between USA and Netherlands appears to be a classic holding race. However, the computer model categorizes this duel as WPHBC due to a very small, short lead by Netherlands in the first 20 meters. At 770 meters, the USA drive slows, making this a hold point with USA sitting on a decisive 4-second lead. The Netherlands challenge drive does not begin until 1100 meters – a point at which the USA stroke rate now dips below the Netherlands. The USA responds to the challenge at 1470 meters. As they enter the last 500 meters, USA holds off Netherlands for 200 meters while they temporarily overstroke Netherlands slightly. Netherlands

regained the higher stroke rate over the last 300 meters and start to drive again, but it is too late to catch USA. Judging from the slope of the Dutch challenge drive, the USA needed to respond when they did. Had the Netherlands challenge drive continued at its rate from 1100 to 1470 meters, they would have caught the USA before the end of the race.

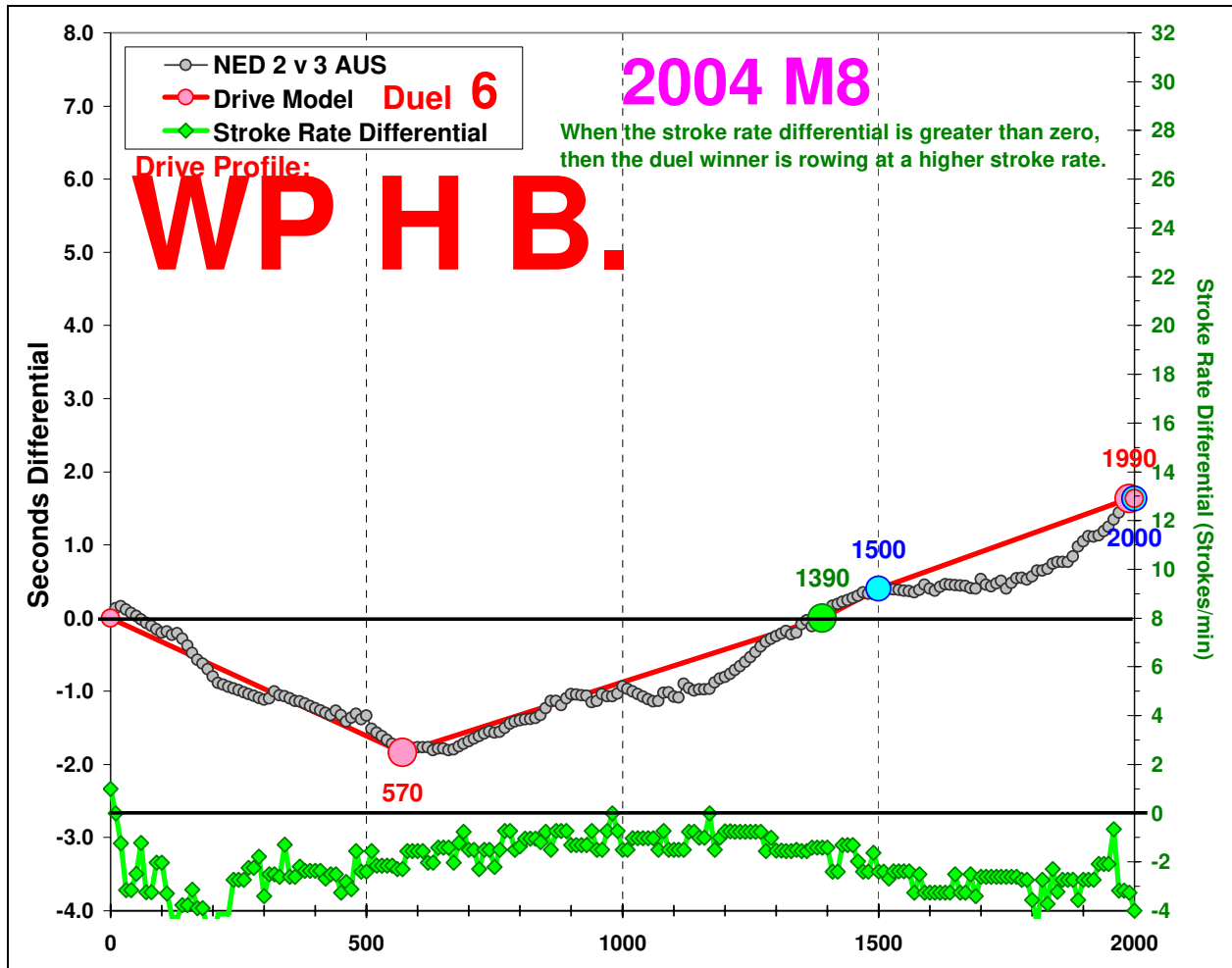


Figure 4-20: 2004 M8 Drive Model of the Silver Medal Position duel

While falling short on its drive to catch USA for the gold medal, Netherlands was also dueling for the silver medal against Australia. Netherlands understroked Australia by 2 to 4 strokes over the first 570 meters during which the Australians built nearly a 2-second lead. In the middle 1000 meters, Netherlands mounted a decisive drive to catch Australia by 1390 meters. This was accompanied by a narrowing of the stroke rate differential. At 1500 meters, Australia increased its stroke rate advantage and was able to keep the race close at about a half second gap. In the last 200 meters, the Netherlands extended its lead to almost 2 seconds.

Netherlands rowed a classic come-from-behind even-paced race strategy – spotting Australia a big lead over the first 500 meters, driving steadily over the middle 1000, and remaining strong at the finish for the silver medal.

Case 5: 2007 World Championship Men's Eights Finals (2007 M8)

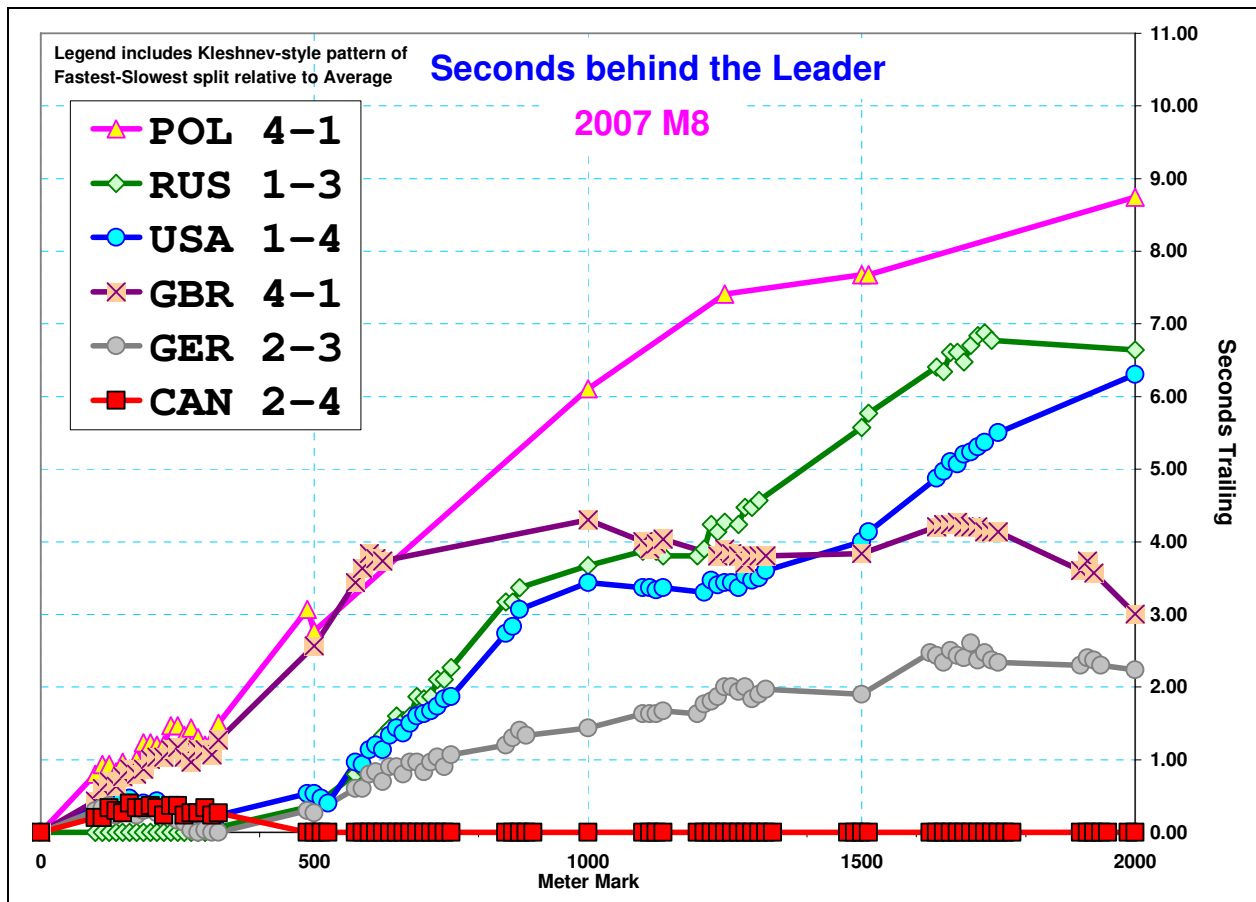


Figure 4-21: 2007 M8 Race Progress in Terms of Distance behind the Leader

Russia and Germany battled each other for the lead over the first 500 meters. Canada gained the lead around 500 meters and held it the rest of the race. Germany drove to a decisive lead for the silver medal in the second 500 meters pulling quickly away from USA and Russia. Great Britain was in last place at 600 meters, but put on a drive in the second half of the race to take the bronze and challenge for the silver. (Russia would later be disqualified from this race after the team tested positive for banned substances, but their results are still analyzed here. Whatever illegal benefit they may have received seems ineffective after the first 500 meters.)

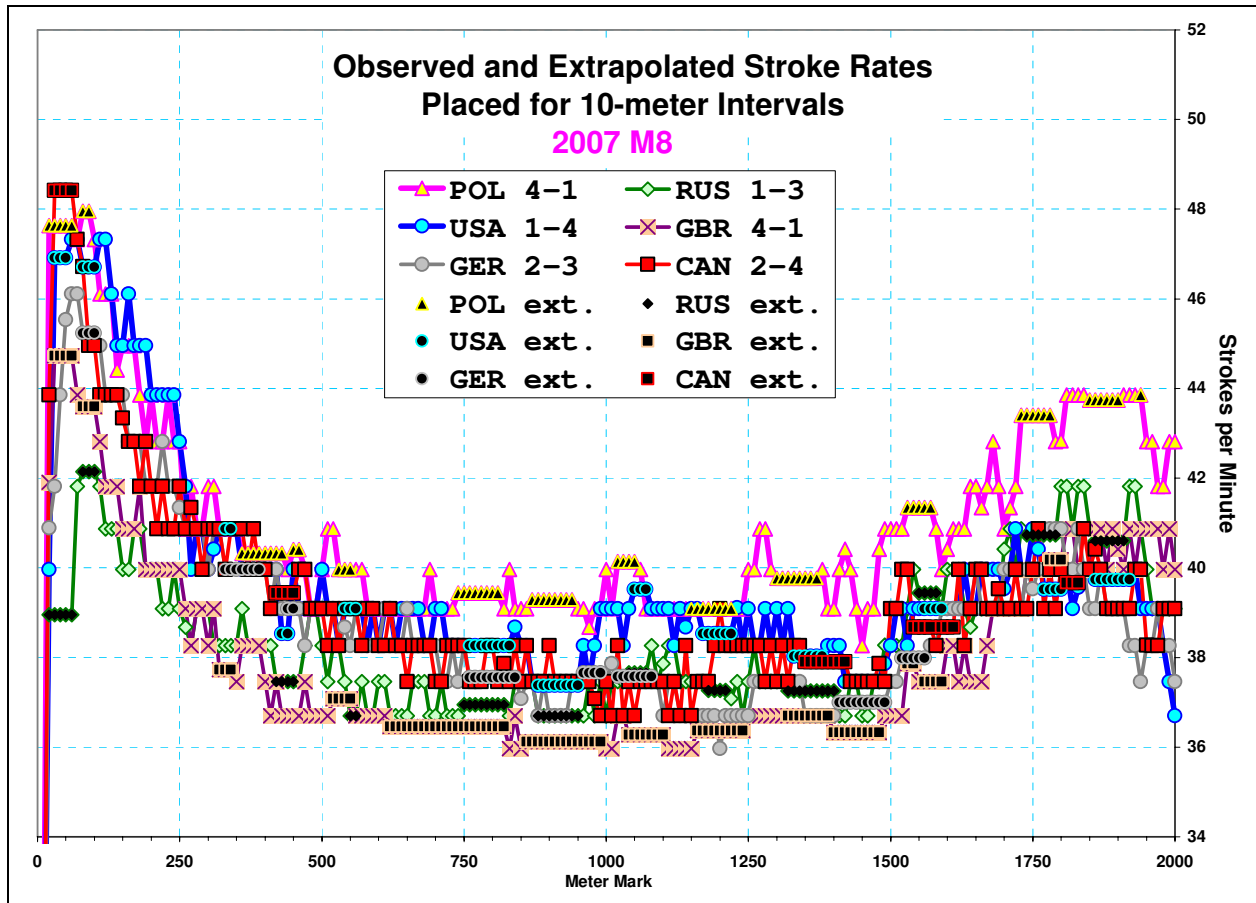


Figure 4-22: 2007 M8 Stroke Rates of Each Crew down the Course

Canada won gold by rowing at moderate stroke rates compared to the other crews. Germany did similarly. Great Britain understroked everyone else most of the race until the last 250 meters where their sprint was higher than most. Poland seemed to be following a strategy to overstroke its competition throughout the race, and especially at the end. Perhaps, the gearing on their oars was too light. They were never in contention, and challenged Great Britain for fifth place only for the first 600 meters until Great Britain began their come-from-behind drive for the bronze. The USA overstroked everyone including Poland for most of the first 250 meters.

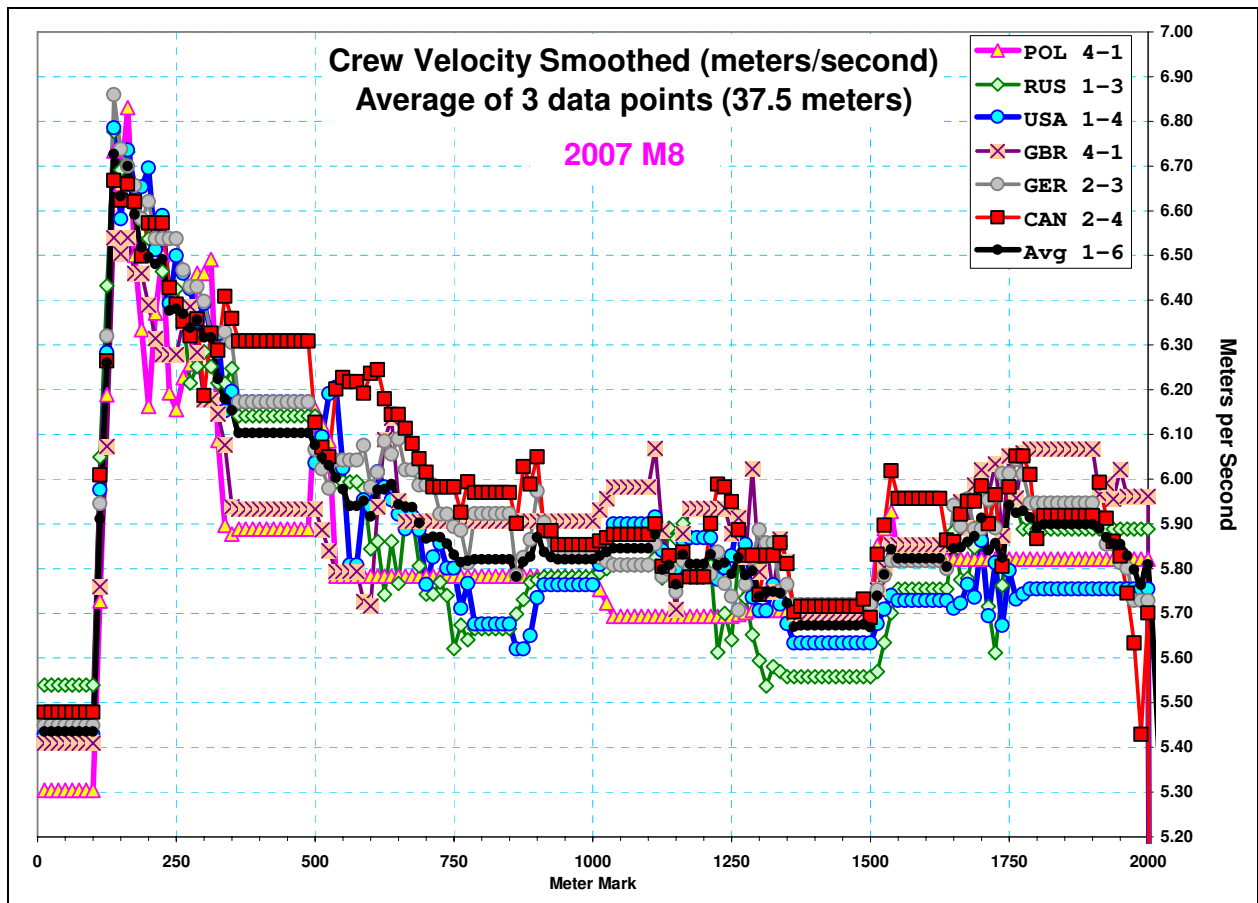


Figure 4-23: 2007 M8 Crew Velocities down the Course

Canada was fast throughout the race. Great Britain drove on them for 200 meters around the 1000-meter mark, and then for the last 250 meters of the race. USA showed speed for the first 300 meters during their high stroking start. Afterwards, they generally were slow, except for about 300 meters after the 1000 – during which their stroke rate also significantly increased. After this drive, the USA faded quickly and just barely held off Russia in the duel for fourth place.

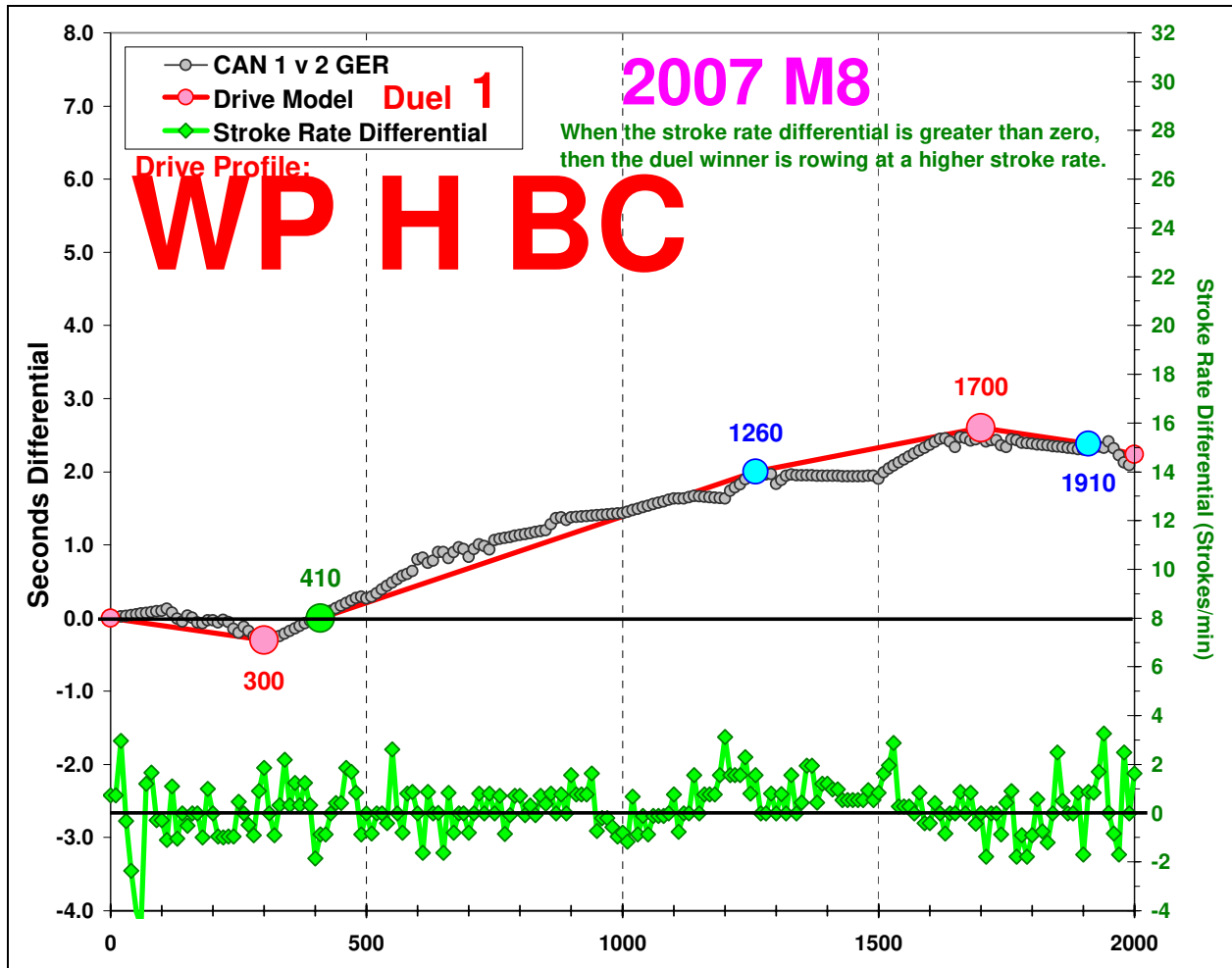


Figure 4-24: 2007 M8 Drive Model of the Gold Medal Position duel

Canada followed the generic WPHBC drive model spotting Germany a slight lead during the start. After 300 meters, they came from behind and caught Germany at 410 meters. Canada steadily built its lead reaching a hold point at 1260 meters with over a 2-second lead. Canada achieved its best lead at 1700 meters gaining almost a 3-second advantage. Germany put on a slight challenge in the last 300 meters, but not seriously threatening Canada's decisive lead. Stroke rates fairly closely tracked each other throughout the race.

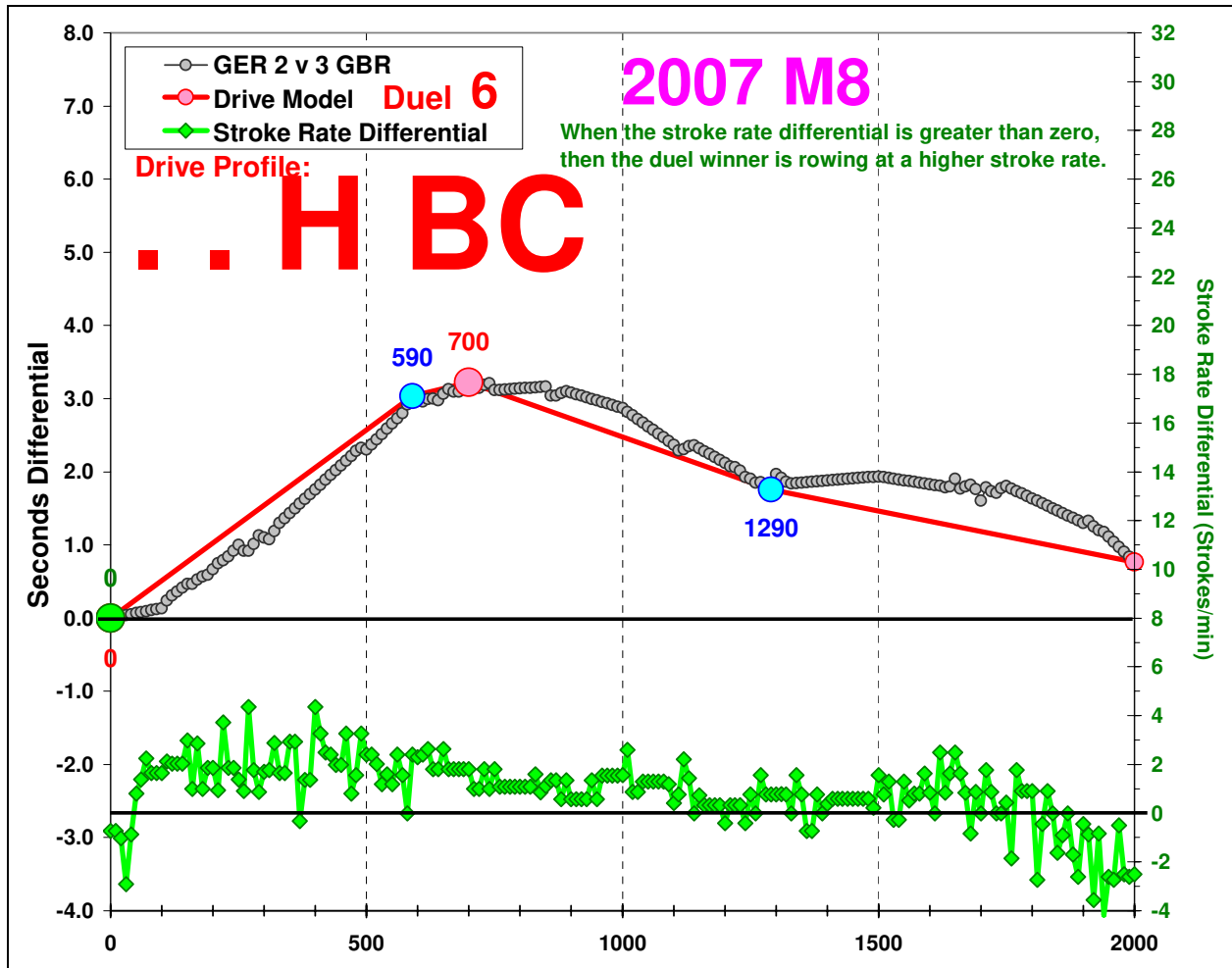


Figure 4-25: 2007 M8 Drive Model of the Silver Medal Position duel

In the last half of the race, Germany's attention may have been focused on holding off Great Britain for the silver rather than trying to catch Canada for the gold. The duel for silver was a classic HBC holding race for Germany. Great Britain fell behind Germany by a decisive margin of over 3 seconds by 700 meters. Great Britain then started their challenge drive. At 1290 meters, a challenge point is reached where Germany needed to respond. Otherwise, the rate at which Great Britain was closing would lead to their catching Germany before the end of the race. Germany responded at the 1290-meter point by holding a 2-second lead against Great

Britain for the next 500 meters. For the last 250 meters, Great Britain finished with another challenge drive, but it was too late and Germany took won the duel for silver by less than 1 second.

*What is to be sought in the display of information
is the clear portrayal of complexity.*

Edward Tufte
(Tufte, 1983, p.191)

CHAPTER FIVE: DATA ANALYSIS AND INTERPRETATION

Position Duel Combinations

With six teams per race, there are a total of 15 combinations of crew pairs competing against each other (see Figure 5-1). These can be thought of as 15 separate duels. However, the focus of each crew during the race is usually on trying to pass the nearest crew ahead of them, and simultaneously, to holding off the nearest crew behind them. Ultimately, the final order of finish defines the five most decisive “position duels” in each race.

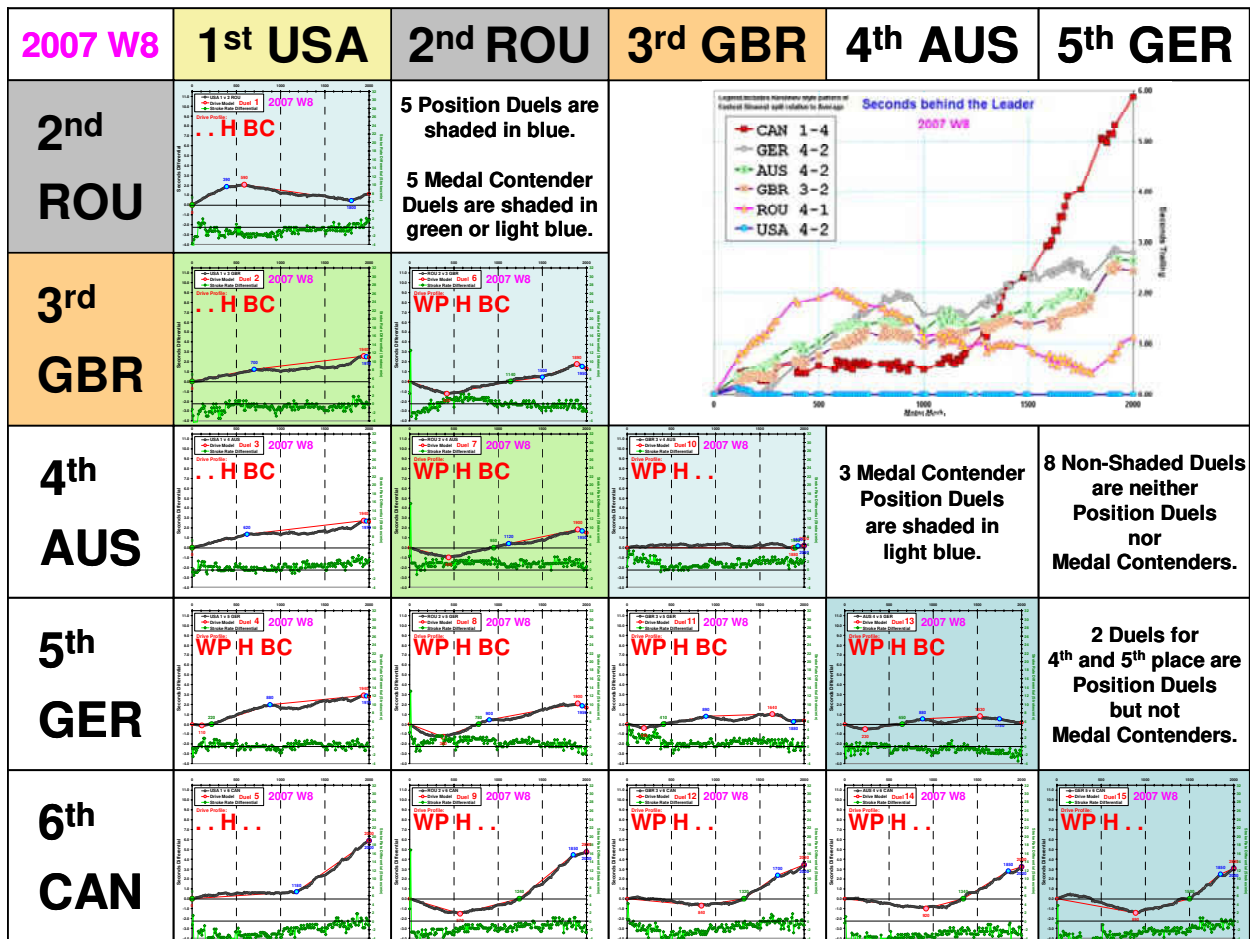


Figure 5-1: Profile of all 15 Duels in a Race among 6 Crews

The position duels are shown along the middle diagonal in Figure 5-1. Although crews may change positions throughout each race, these five position duels and how they performed against each other are suggested to be the most meaningful races to study for analytical purposes.

Figure 5-1 profiles all 15 duels from the 2007 Women's 8 Final. These are coded to reflect the presence or absence of the various points that define the segments from the generic drive model. Duels coded as "WPHBC" can be seen to have all five points that define the boundaries between each component of the drive model. In other words, they all have a (**W**) worst margin point, (**P**) passing point, (**H**) holding point, (**B**) best margin after passing point, and a (**C**) challenge point. The simplest of races only have a single point (**H**) that differentiates an acceleration point at which the pace of the winning drive changes in velocity. For example, the duel between USA and Canada in Figure 5-1 has only an **H** point. Canada never gained the lead and never made an observable challenge drive to close the gap, although they kept the race close for the first half of the race.

Appendix E summarizes all of the race-pair duels from all 5 races studied – containing a total of 75 duels. "Position duels" are the most competitive races since they determined the exact order of finish. An alternative to studying position duels would be to study "medal duels" based on the presumption that crews out of contention for a medal might perform differently than medal contenders. Appendix F summarizes the pattern of drives for position duels and medal duels. Appendix G adds shading to the drive patterns to illustrate which races follow a holding race pattern. The number of races studied in this research is not sufficient to draw reliable conclusions about the relative advantages of studying position duels versus medals duels. This dissertation focuses on position duels for purposes of studying the patterns of drives in a race.

The Taxonomy of a Drive: Decisive versus Challenge Drives

For purposes of this research, when one crew is closing the gap on another crew, it is referred to as a drive. It could be that one crew started moving faster, or the other crew started fading and moving slower, or some combination of the two. The reason for a drive may not be known from the observed race data. Regardless of the reason, drives can be identified in a duel, and their patterns of occurrence analyzed.

Drives have starting points, ending points, and sometimes a passing point where one crew passes the other crew. In a duel between two crews, a “decisive drive” is defined to be the drive in which the winner of the duel gained the final lead over the other crew, never to lose the lead afterwards.

The starting point and ending point of a drive can be a subjective interpretation. Crews that gain a significant lead may sit on their lead and adopt a holding race strategy. At this point, the psychology of the race may change. The lead crew may slow down and intentionally or unintentionally reduce the rate at which it continues to drive on the other crew. Alternatively, there may be a point at which the trailing crew changes its strategy from trying to catch the leading crew in a duel to holding off a third crew. This can result in an acceleration point where the lead crew increases the rate at which it is driving on the other crew. In studying the drive pattern of a duel, the race analyst may need to subjectively identify the acceleration points that define the starting or ending point of a drive.

There is an alternative to subjectively defining the starting and ending point to a drive. One could use the worst moment (**W**) and the best moment (**B**) for the winning crew in a duel. This is where the gap between the winning and losing crew in a duel is the smallest and the

largest. Those two moments define the starting and ending point of the “total gap” closed between these crews. Studying this total gap accurately measures the total distance closed, but tends to lower the slope or rate of change that one crew moved on the other. This underestimates the rate at which crews are able to close on each other in a duel. Therefore, for this research, drive start and end points are subjectively selected based on the observation of acceleration points where race behavior (and perhaps the race psychology) appears to change.

Crews that lose a duel can also make a drive on the winner. These are defined as “challenge drives.” A challenge can happen early in a race as the losing crew is spotted a lead (that it eventually loses). A challenge drive can also occur later in a race as the losing crew attempts to come from behind and close the gap on the winner of the duel. Similar to decisive drives, the start and end points of a challenge drive can either be subjectively defined based on acceleration points or objectively identified as the total gap closed. Again, for this research, the challenge drive is judgmentally selected to reflect where drive slope changes appear significant.

Whereas every race duel has one and only one decisive drive, some losing crews never do challenge the leader. The lead crew could pull steadily ahead of the losing crew, and in so doing, there may never be a point in the duel where the challenger ever begins to close the gap on the leader. Therefore, a challenge drive might not happen in any given duel. In other duels, there may be multiple challenge drives, in which case the most dangerous drive should be subjectively chosen as the challenge drive to be analyzed and interpreted.

By limiting the modeling and analysis of race drives to only the five decisive drives in a 6-boat race, it eliminates consideration of many trivial duels where crew pairs are never effectively competing against each other. For instance, the gold medal crew may steadily pull

away from the sixth place crew without there ever being a meaningful challenge drive.

However, the fifth place crew may have had a neck to neck duel with the sixth place crew, perhaps even more challenging and dramatic than the duel between the first and second place crews. Any crew that makes it to the finals of a world championship is an extremely competitive crew – and well worth studying even if they are only battling for fifth place.

Figure 5-2 illustrates the locations of the decisive drives (shaded in green) and the challenge drives (shaded in pink) identified in each of the 25 position duels in the 5 world championship races studied. Each duel contains a decisive drive and a challenge drive, although the location and magnitude of these drives varies considerably from race to race. The pattern of these drives reflects a balanced diversity in drive profiles when compared vertically among the race classes (men, women and lightweight competition) and horizontally among the position duel types (for first through sixth place). In other words, it is not obvious that studying the pattern of drives would benefit from a stratified analysis differentiating between men and women's competitions, or between medal duels and the position duels for lesser positions.

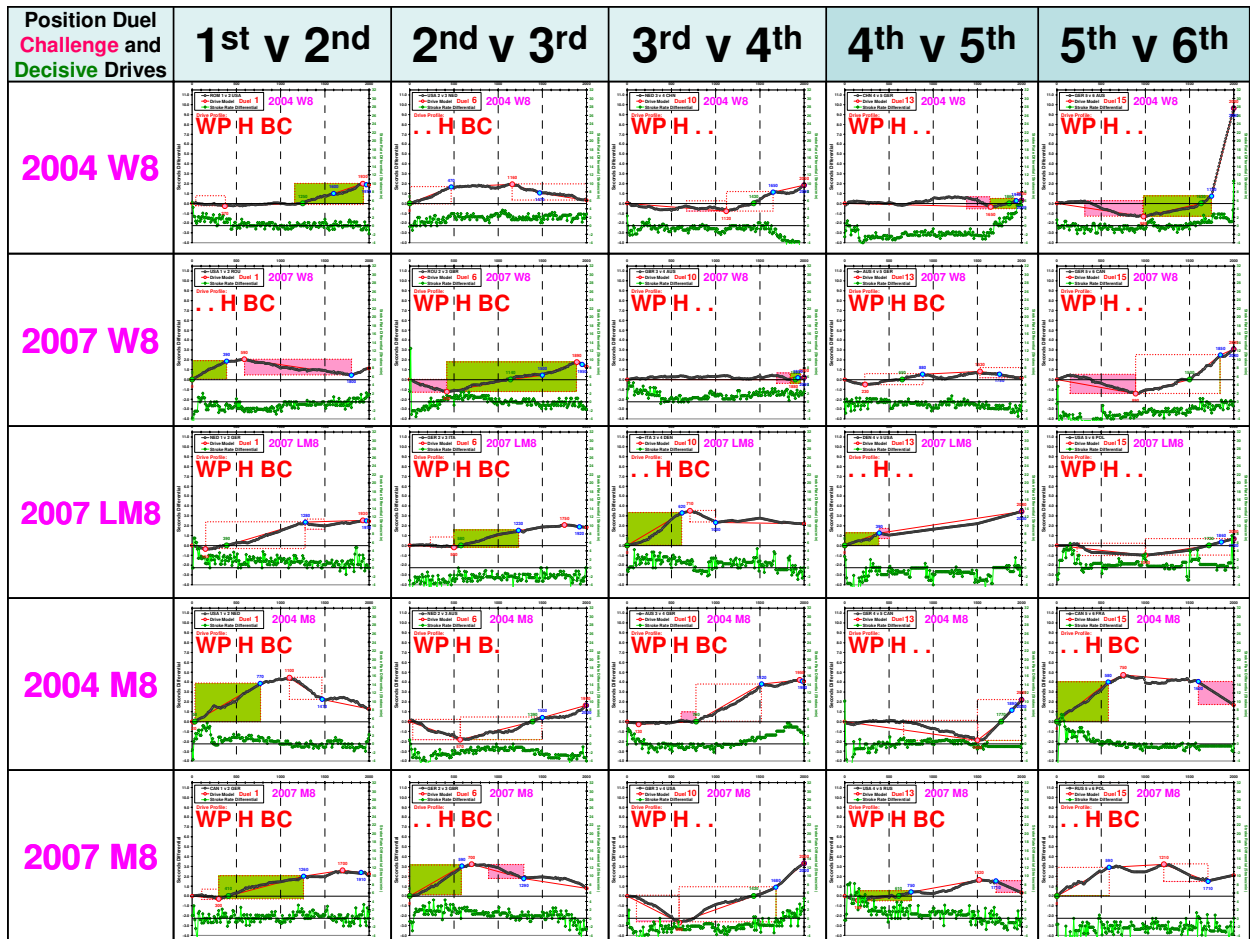


Figure 5-2: Decisive and Challenge Drives from the 5 Position Duels in each of 5 World Championship Races

Drive Patterns

Figure 5-3 illustrates the overall pattern of the “decisive drives” from the 25 position duels studied. The pattern of decisive drives is more clearly illustrated by placing all these drives onto the same graph. Some general observations about the pattern of these decisive drives:

- 32% (8 of 25) of the decisive drives began at the start of the race. The rest of the drives began at various points all across the 2000-meter distance. The duel between Great Britain (3rd) and Australia (4th) in the 2007 women’s championship was not decided until the last 100 meters of the race.
- Only 24% (6 of 25) of winning crews needed to make up more than a 1-second gap spotted to the eventual losing crew. Only one winner (Great Britain over USA for third place in the 2007 lightweight competition) spotted more than a 2-second lead.
- 64% (16 of 25) of winning crews reached a holding point before gaining more than a 2-second lead. Only one winning crew (Canada over France for 4th place in the 2004 Olympic men’s final) gained as much as a 4-second lead before reaching a holding point.

Overall, most winning crews in a duel do not spot the losing crews more than a 2-second lead before the decisive drive in which they gain the lead themselves. After passing the other crew, winning crews eventually reach a holding point where their drive-slope behavior (an acceleration point) suggests confidence in their ability to hold this lead and react as needed to any challenges by the losing crew.

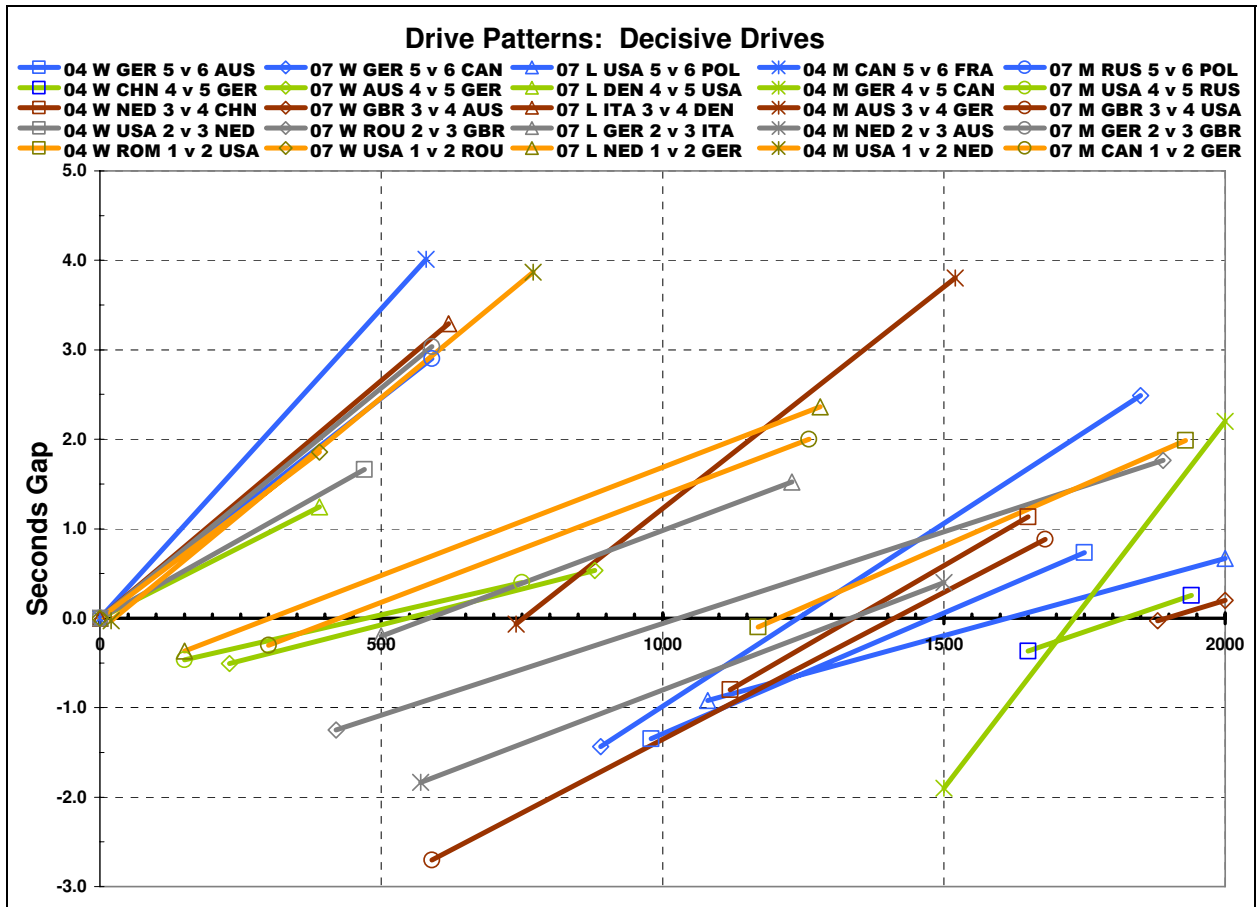


Figure 5-3: Decisive Drive Patterns over 5 Races (the 25 "Decisive Drives")

Figure 5-4 illustrates the overall pattern of the “challenge drives” from the 25 position duels studied. Some general observations about the pattern of these challenge drives:

- 56% (14 of 25) of the challenge drives resulted in the losing crew taking a lead in the duel. This means that a majority of duels were won by coming from behind after the winning crew spotted the losing challenger a lead.
- In all (14 of 14) of challenge drives that gained the losing crew a temporary lead, the losing crews began their drives having to close no more than a .58 second lead before gaining this lead.
- 86% (12 of 14) of challenge drives that actually result in a lead have passing points where the lead is gained by the challenger in the first 700 meters in the race.
- 73% (8 of 11) of challenge drives that failed to gain a lead were still able to close a gap of at least 1.19 seconds.

Overall, it appears that challenge drives are most effective at gaining a temporary lead when they occur in the first 700 meters of the race and when the gap they need to close before gaining the lead is minimal (less than .58 seconds).

The “challenge totals” for a duel measure the maximum gain that the losing crew was able to move on the eventual winning crew. This includes not only selected challenge drive segments, but also other additional gains that may not be contiguous or at the same rate as the challenge drive. See Appendix I for a comparison of challenge drives versus challenge totals, and see Appendix H for a similar comparison of decisive drives versus decisive totals.

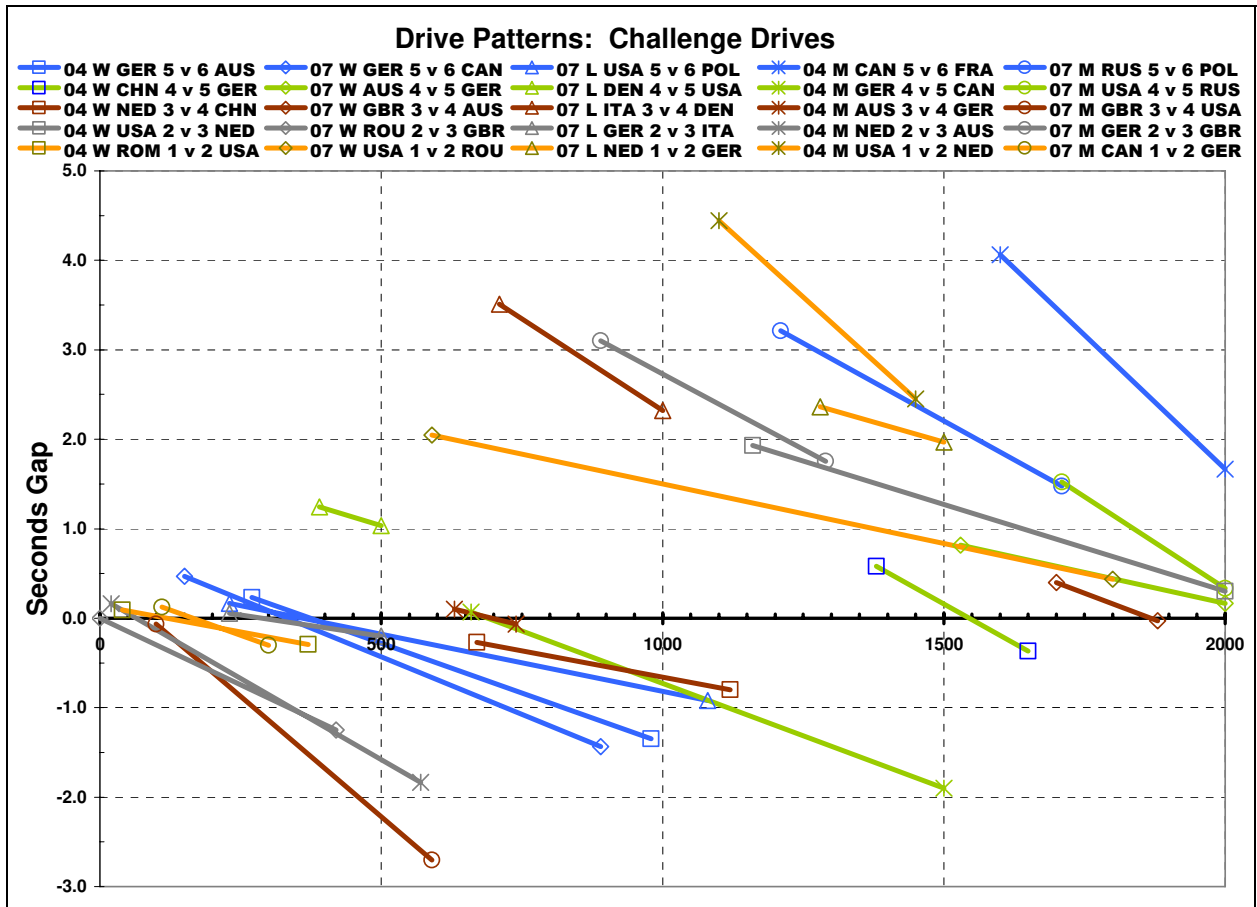


Figure 5-4: Challenge Drive Patterns over 5 Races (the 25 "Challenge Drives")

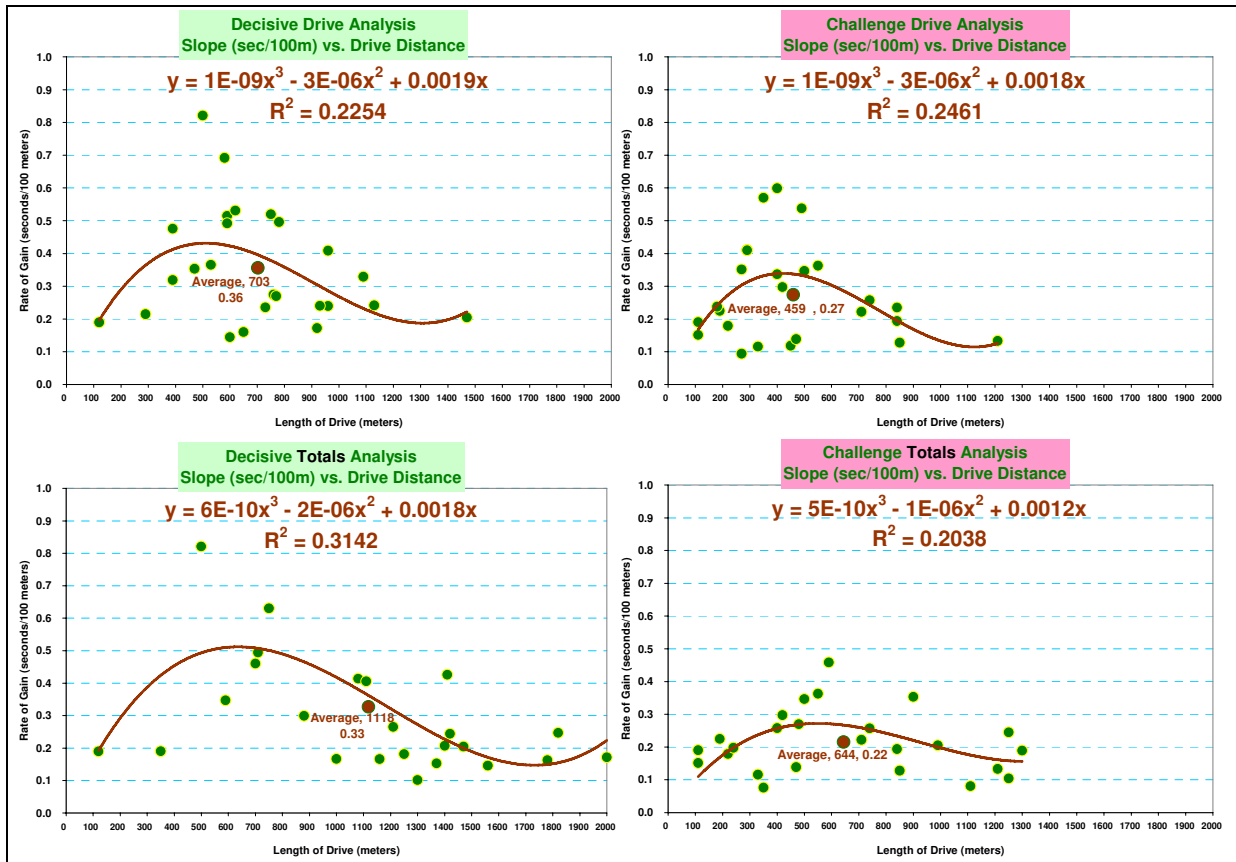


Figure 5-5: Decisive Drives and Totals versus Challenge Drives and Totals

Figure 5-5 summarizes the four combinations of decisive vs. challenge drives, and drives vs. totals. Third order polynomial trend lines are overlaid onto these graphs. For the 25 position duels studied, the average durations are longer and the average slopes are flatter for the totals trends than the drives trends.

The average durations are longer and average slopes are steeper for the decisive trends than the challenge trends. Perhaps coincidentally, the second and third order curvature parameters for decisive drives and challenge drives are identical.

The degree of curvature of challenge totals is much less than the other three graphs.

Winning Margins in a Duel

As explained above, the pattern and slope rates of drives can vary substantially from duel to duel. The magnitude of leads held or overcome also varies. Figure 5-6 illustrates the margins in seconds by meter mark of the winning crews ahead or behind the losing crews for all 75 duels in the 5 races studied.

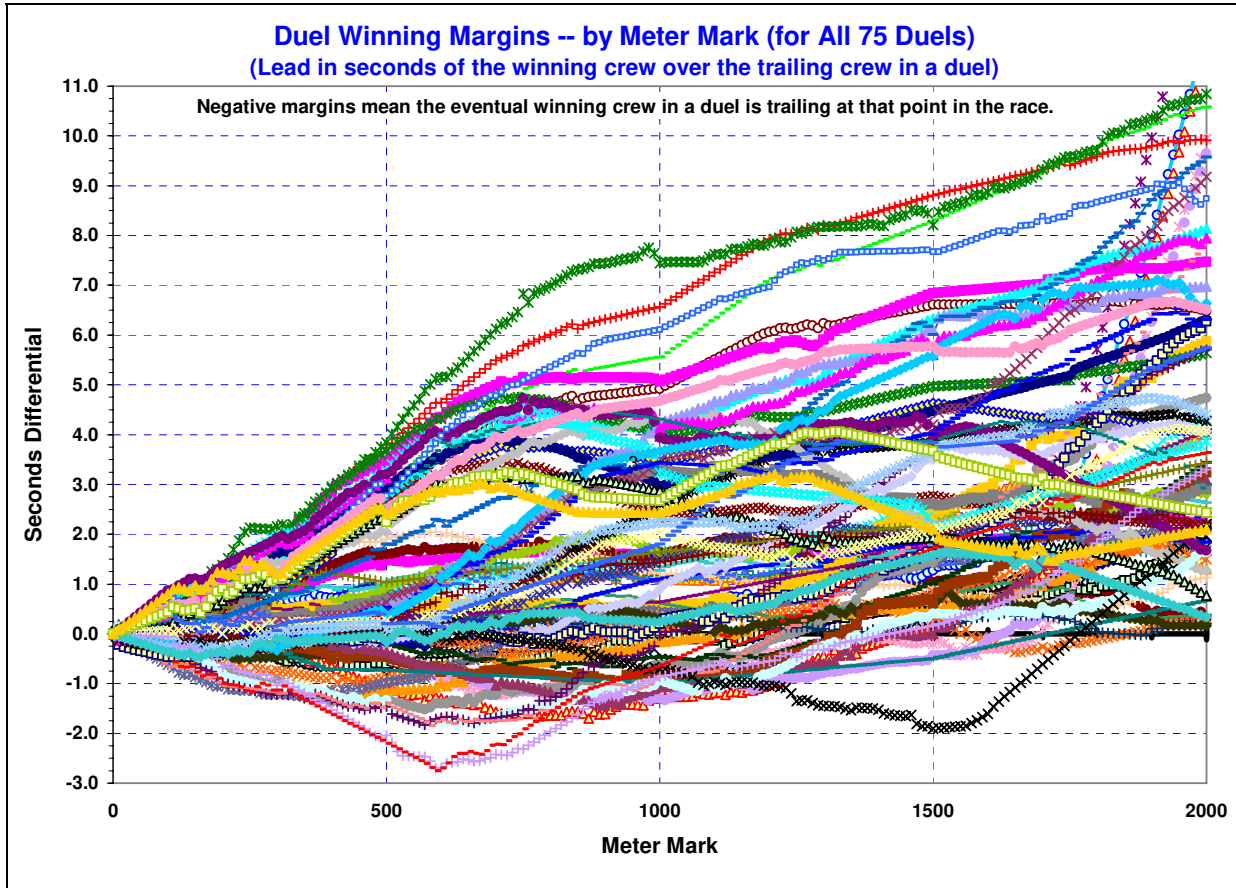


Figure 5-6: Winning Margins by Meter Mark for all 75 Duels in 5 Championship Races

Although the mass of data in Figure 5-6 is difficult to visually interpret, some general observations can be seen:

- Winning crews may spot their opponent(s) a lead before catching them later in the race.

- The magnitude of winning margin varies throughout the duration of the 2000-meter duel with some of the winning margins being quite large (11 seconds or more) by the finish line.

How crews drive on each other has already been analyzed and illustrated earlier in this paper. What can also be studied is the pattern of winning margins in a duel. Figure 5-7 takes the data from Figure 5-6 and summarizes it in terms of percentile contour lines. There are a total of 75 observations at each meter point for all 15 duels from each of the 5 races studied. These 75 observations allow percentiles to be calculated for how much of a lead the winning crew in a duel typically has over its opponent.

Note that this percentile analysis considers all 15 duels in a race. Therefore, it includes lopsided races including the margins of the gold medal crews over the last place crews in a race. In future studies with larger race sample sizes, these contour lines could focus in on only the position duels or even just the gold medal position duels. Nevertheless, by considering all the duels as is done in this research, this data is representative of the margins that a typical world championship finalist crew in 8's competition is capable of gaining over another typical finalist crew.

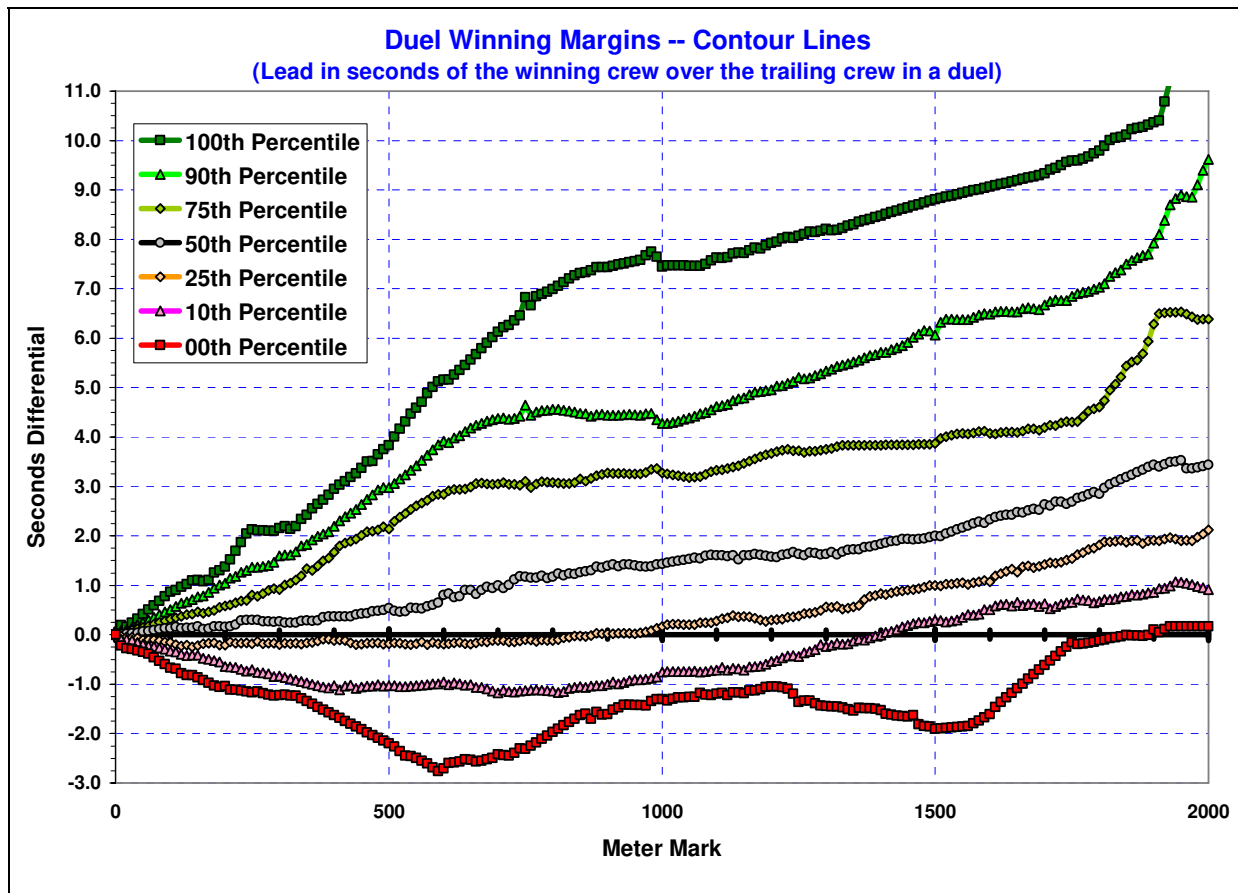


Figure 5-7: Winning Margin Percentile Contour Lines

Some observations from these winning margin percentile contour lines:

- In 10% of all duels, the winning crew can be expected to trail its opponent for most of the race, and will not gain the lead until some point in the last 600 meters.
- In 25% of all duels, the winning crew may not take the lead until some point after the 900 meter marker.
- For the second closest quartile of duels (comparing the 50th percentile and the 25th percentile lines), the race will be very close for the first 1000 meters. The winning crew may trail for a small fraction of a second or lead by up to 1.5 seconds, before pulling away in the last 1000 meters to win by a margin ranging from 2 to 3.5 seconds.

- For the top 10 percentile of most lopsided duels, the winning crew pulls steadily away from its opponent gaining a lead of 3 to 4 seconds by the 500-meter mark, and ultimately winning by a margin of over 9 seconds.

Probabilistically Decisive Lead

The contour lines in Figure 5-7 show the distribution of what ultimately happens in terms of the margin in seconds of the lead crew over its opponents in a typical duel. However, it does not show the likelihood of winning a duel as a function of gaining or trailing at a given point in a duel. Figure 5-8 illustrates the conditional probability of winning a typical duel for a crew that is trailing by varying amounts at different points in a race. (Flip the graph upside down to see the inverse conditional probabilities for a crew that is leading in a duel to still hold a lead at the finish line.) Appendix J provides more examples of the probabilities of eventually winning when trailing in a duel at some point in the race by varying time gaps.

Figure 5-8 shows conditional probabilities of coming from behind that vary by position on the course and the amount of lead one crew has over another in a duel. Some observations:

- When the race is close (see red line graphing leads of 1 second or less), this lead does not become probabilistically decisive until late in the race. For the first 1350 meters, a lead of less than 1 second is an advantage, but the trailing crew in a duel can still overtake the lead crew between 36% and 49% of the time.
- A lead of 1-2 seconds is a more probabilistically decisive lead (see green line). After 1250 meters, there is no better than a 6% chance that the trailing crew in a duel will overcome this gap. The lead is less decisive earlier in the race. For the 75 duels studied, on those occasions when a crew held a 1-2 second lead between 350 and 950 meters, there is at least a 31% chance of coming from behind to win the duel.

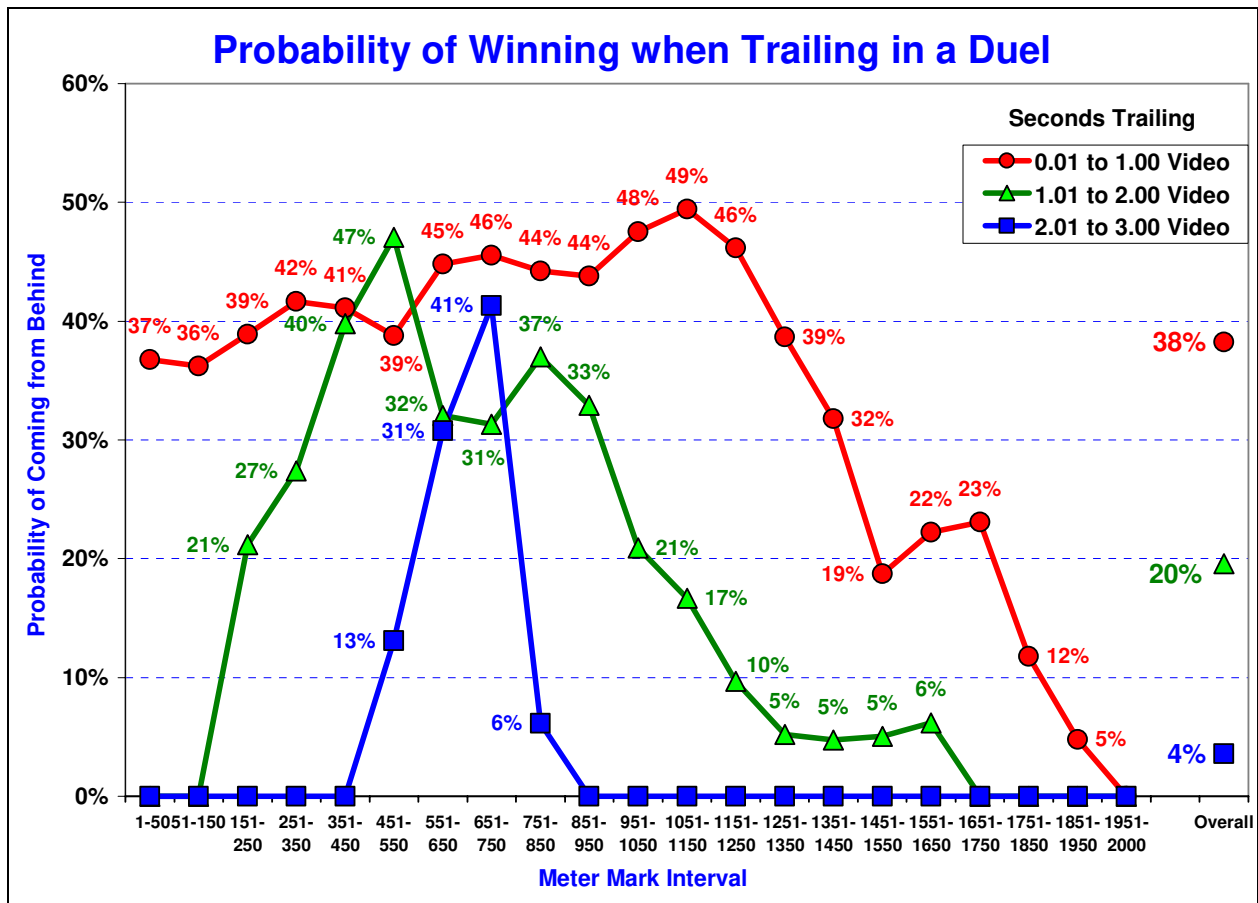


Figure 5-8: Probability of Coming from Behind based on Video Analysis of 75 Duels

- A lead of greater than 2 seconds in a duel proved very decisive in the 5 races studied (see blue line). Only in one interval (between 550 and 750 meters) did this lead not prove highly decisive. For the 75 duels studied, on those occasions when a crew held a 2-3 second lead between 550 and 750 meters, there is a 31 to 41% chance that the trailing crew would eventually win the duel.
- The probability of holding a lead or losing a lead can be aggregated overall. On average over the 2000 meters, a crew holding less than a 1-second lead will lose this lead and the

duel 38% of the time. A lead of 1-2 seconds will be overcome by the trailing crew only 20% of the time. A lead of 2-3 seconds will be overcome only 4% of the time.

These probabilities are derived through video analysis of 5 championship races that included a total of 75 duels among a total of 30 competing crews. Further video research adding many more races will improve the reliability of this analysis. Until more video races can be researched, the validity of these statistics can be tested by analyzing the reported official 500-meter splits of a larger set of races. Figure 5-9 overlays conditional probabilities derived from analyzing the reported splits from all 21 world championship and Olympic eights races from 2001 through 2008 (including the 5 races studied through video analysis). The splits-based analysis includes a total of 315 duels among a total of 126 competing crews.

Surprisingly, the overall averages for video and splits probabilities are very close to each other – within 1 percent – for each of the three seconds trailing measures. This supports the notion that the video sample and the splits sample both represent similar data sets in aggregate – although the details fluctuate over the different portions of the 2000-meter course.

It is difficult to compare the raw results of video analysis versus the splits analysis. The small sample size of the video analysis results in widely fluctuating probabilities even though the video analysis is aggregated over 100-meter intervals. In some cases, the video probabilities are close to those calculated from the 500-meter splits, but in other cases, the results vary widely.

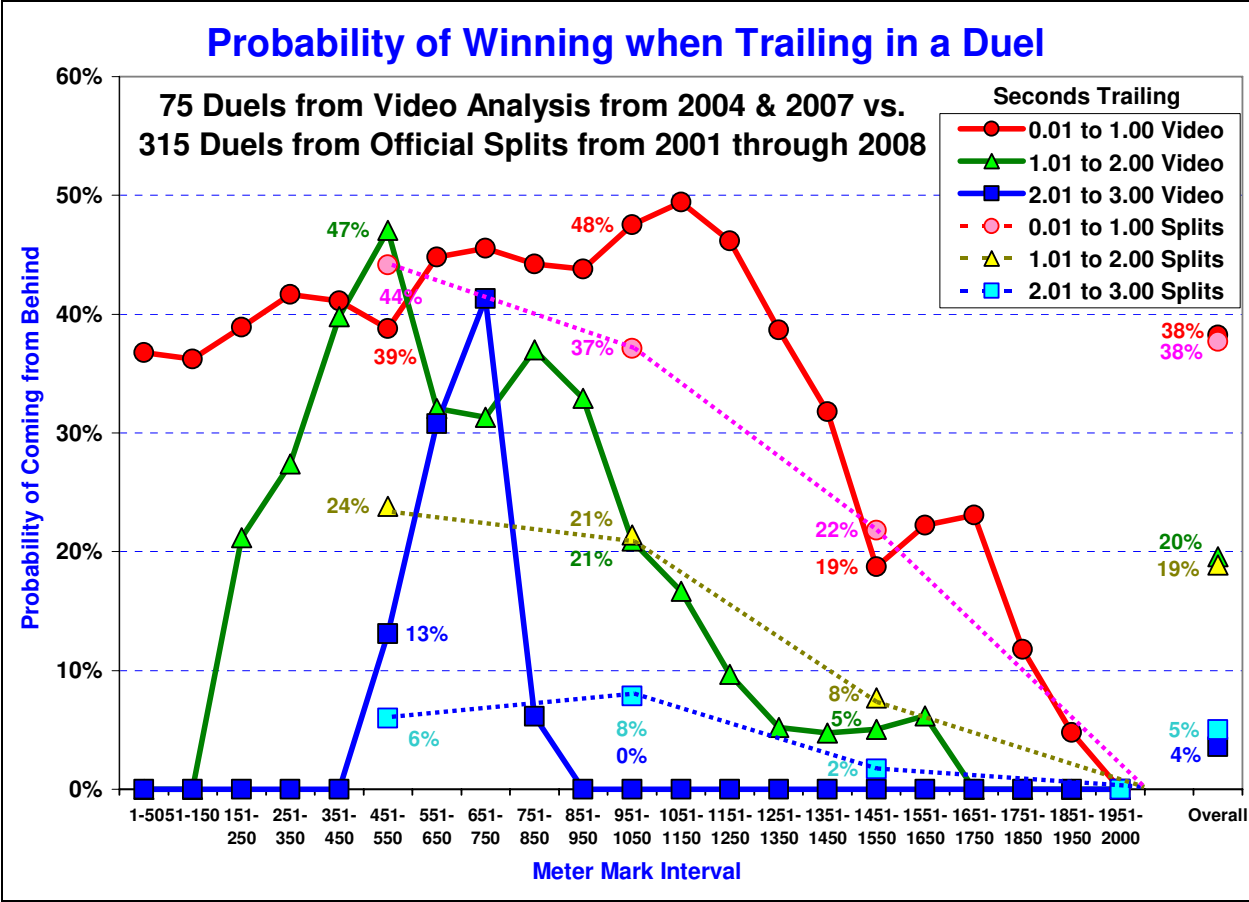


Figure 5-9: Probability of Coming from Behind overlaying an Analysis of Splits from 315 Duels

Probability of Winning when Trailing in a Duel

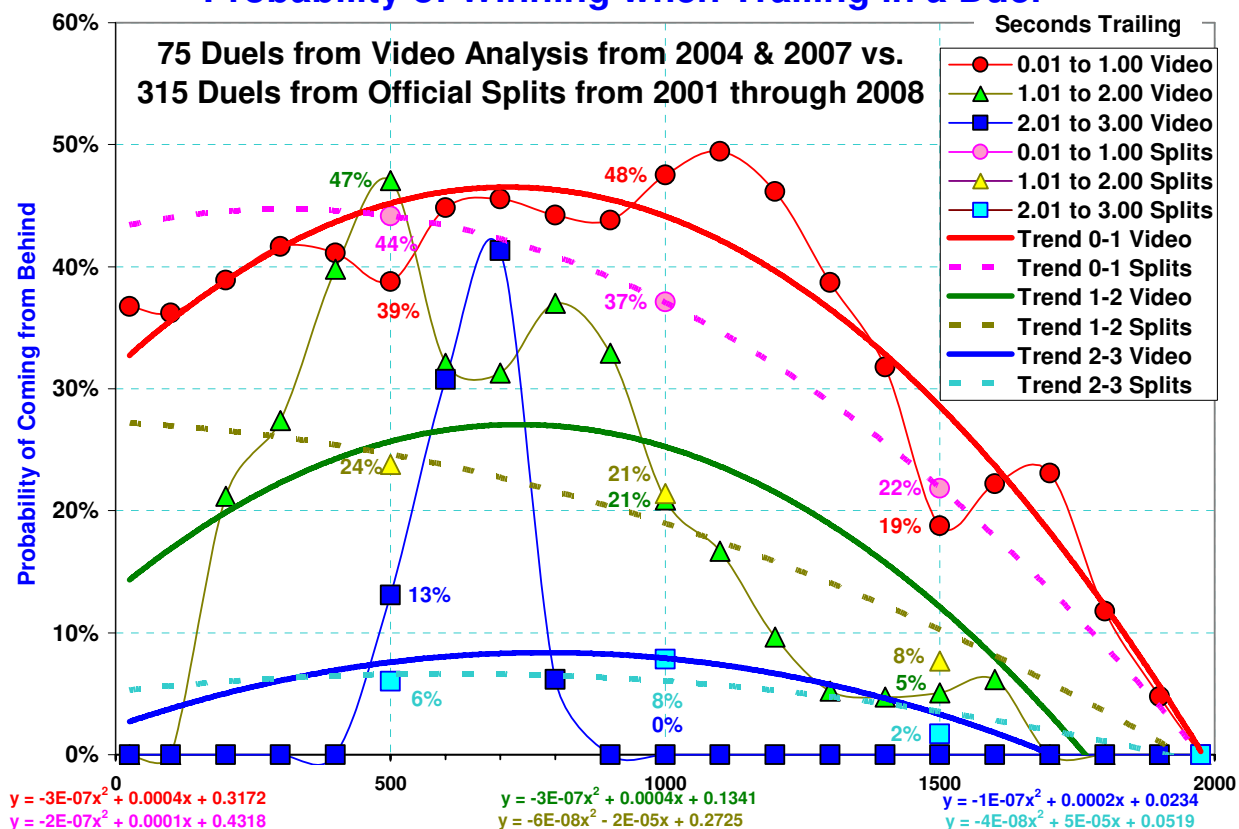


Figure 5-10: Probability of Coming from Behind overlaying 2nd Order Polynomial Trend Lines

Overlaying trend lines onto both the video and splits based data helps greatly in comparing the results of these analyses. Figure 5-10 adds second-order polynomial trend lines to the data shown in Figure 5-9. This is a very busy graphic. To aid in visualizing this data, Appendix K breaks this graph down into separate analyses for each of the three seconds-trailing ranges studied.

All six trend lines show concave curves. However, the splits-based curves are much shallower than the video-based curves. The R-squares values (see Appendix K) show a good fit of these trend lines to the data for each of the splits-based strata. This is not surprising given the

small number of data points (four) for which these 2nd order polynomials are being fit. The r-squares value for the video-based curves is high for the 0-1 seconds trailing range, but a poor fit for leads over 1 second.

Comparing the results of the video analysis to the splits analysis, several general patterns can be seen:

1. The average height of trend curves appears to be about the same when comparing splits versus video results. This is consistent with the previous measurements of the overall probabilities of winning when averaged over the entire 2000-meter course.
2. The major difference between the splits-based and video-based curves is the second-order parameter measuring the degree of curve in these trends. The four splits-based observation points start at 500 meters and end at 2000 meters, but do not contain any observations within the first 500 meters. Video analysis contain one quarter of all observations within the first 500 meters. The effect of including observations within the first 500 meters appears to pull the curve down within the first 500 meters.
3. There is a poor fit of the second-order polynomial to the video analysis for leads of over 1 second. This might be due to the random effects of the small sample size of this video study. However, it might also be due to the fact that a second-order polynomial is not a good model of the ability of a crew to come from behind – especially in the range from 250 to 950 meters into the race.

One finding that seems common between the splits-based and video-based studies is that small leads of less than 1-second are not nearly as probabilistically decisive as larger leads. Over

the first 1450 meters, small leads of less than 1-second can be overcome at least 32% of the time (based on video analysis). The corresponding splits-based curve drops below 32% around 1250 meters, but the interpretation is the same. Within the last 500 to 750 meters, a 1-second lead becomes much more decisive. As time is running out in a race, there is less opportunity to make a decisive drive. Furthermore, by late in a race, most crews have executed their race strategies, made their tactical drives, and demonstrated what they are capable of doing. A crew holding a lead late in the race has proven itself over a longer distance. Both from a statistical and psychological perspective, crews winning late in the race have reason to be confident of being able to hold a lead – even if just a small lead.

Further video analysis case studies are needed to reliably test whether the differences in the video-based versus splits-based analysis are not simply due to random effects. However, should the video analysis patterns hold up in a larger study, there are three insights supported from this video analysis that are impossible to study from simply analyzing quarterly split data:

1. The video analysis shows a peak just after the 1000-meters. This suggests where small leads are the most vulnerable to opponent drives. Many crews plan in their race strategy to make their “big move” right after the 1000-meter mark. Therefore, this peak may not be a random statistical fluctuation, but rather a behavioral effect of when crews are trying their hardest to challenge for the lead.
2. Leads held within the first 500 meters are more decisive than leads held within the second 500 meters. At first, this seems counter-intuitive. When leads are gained earlier in a race, there is more race time left for the trailing crew to overcome this

- gap. However, the greater decisiveness of a lead gained in the first 500 meters over the second 500 meters may be due to the speed and apparent ease with which this lead was gained. Crews that gain a large lead early in the race may be demonstrating an ability to dominate their opponents.
3. Once a dominant crew builds a decisive lead, it can just sit on this lead and confidently row a holding race from that point forward. A crew that takes longer to build a lead (not until the second 500-meters) may have had to work harder to achieve this lead, leaving it more vulnerable to come-from-behind crews that plan to make their drives later in the race.

This pattern is more apparent with leads greater than 1 second than for crews with small leads. A large lead of over 1 second gained within the first 500 meters is a stronger indicator of dominance. A large lead held within the second 500 meters appears to be more vulnerable to opponent drives – with probabilities of coming from behind as high as 30 to 50% depending on the position on the course.

Another explanation is that a crew that can build a large lead in the first 500-meters often is also be capable of extending its lead into the second 500-meters so that its lead exceeds 3 seconds. Many crews do build leads over 3 seconds in a duel. However, for the 5 races studied by video, no crew had come from behind by over 3 seconds. These large leads with 0% probabilities of coming from behind are not even graphed in this study, since no crew among the 75 duels studied were able to overcome a 3-second lead.

For the splits-based study of 315 duels, only one crew made up this large a gap. That was in the 2005 women's world championships. The Dutch crew trailed the USA crew at the 500-meter mark by 3.63 seconds, but came from behind to win the bronze medal by .27 seconds with the USA finishing a frustrating fourth place. (Since 2005, the USA women seem to have learned from this lesson. In the last 3 years, the USA women's eight have won three straight world championships including the 2008 Olympics – never out of first place on any of their 12 splits – but being challenged by many good crews.)

Effect of Drives on Probabilistically Decisive Leads

The probability of coming from behind in a race is an important element of race strategy and race psychology. A crew's morale is bolstered when a crew is winning or at least within close proximity to the leader. A losing crew's morale can also be significantly bolstered when trailing in a race but currently driving on the competition. Using the results of video analysis, drives can be identified in a race. This drive information can then be used to improve the analysis of probability of winning when trailing in a race.

Probability of Winning graphs can be stratified by whether or not the losing crew is "moving" on the competition. If a crew is moving, its probability of coming from behind is much greater than if that crew is not moving, or worse yet, fading. Figure 5-11 shows the probability of winning when trailing by less than once second, and compares this to a similar probability of winning but restricted to crews that have made drives and improved their race positioning over the last 100 meters along the course. Clearly, there is a major quantifiable benefit of making a drive while behind in a race. See also Appendix L for more examples with different intervals for seconds trailing.

The psychology of the race is such that crews are encouraged by a combination of the magnitude of the position gap and the rate that a crew is closing on another crew. It can be OK to be behind as long as you are capable of mounting a drive on the competition. Detailed video analysis provides the data needed to quantify the effect of driving on the probability of winning.

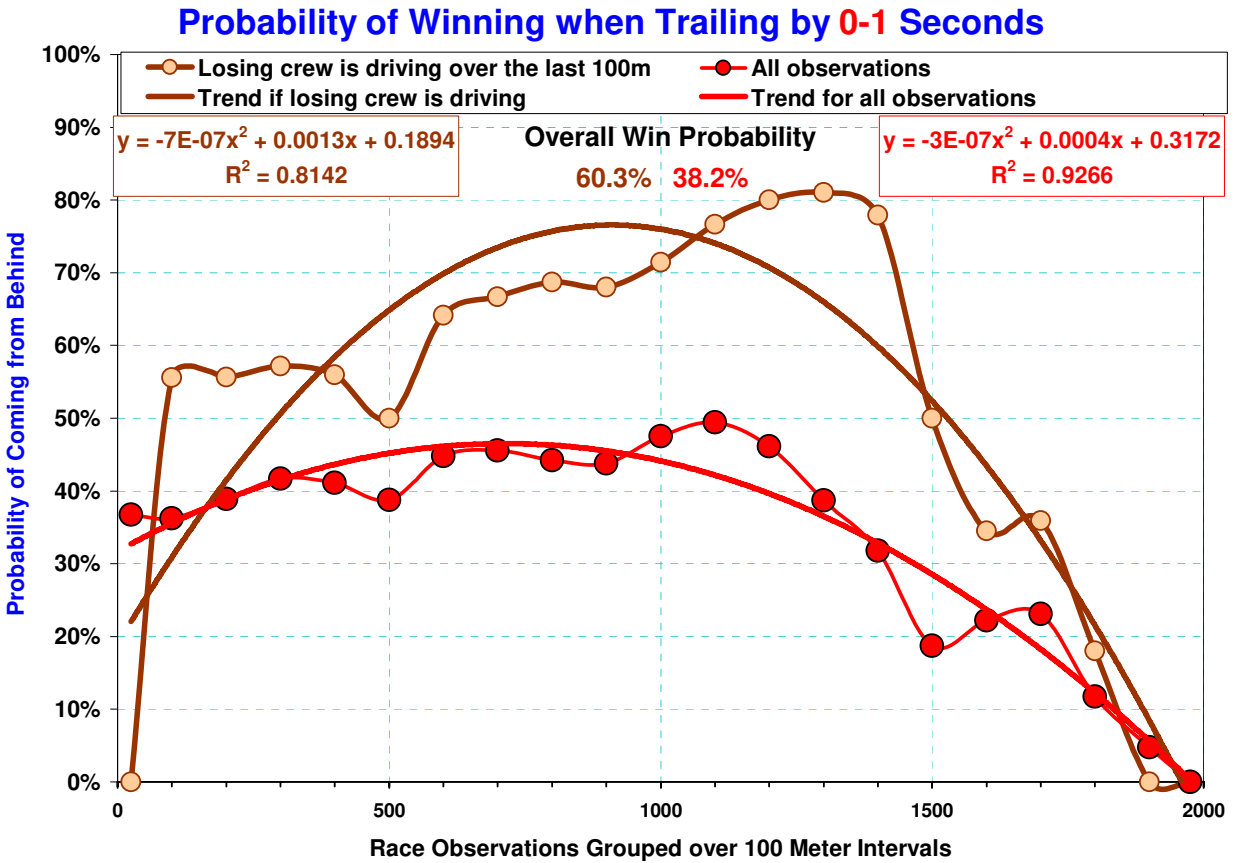


Figure 5-11: Probability of Coming from Behind – Effect of Trailing Crew making a Drive

*When any crew is in position to win a race,
the rowers in that crew will pull harder.*

Don Roock
(Anderson, 2001, p.221)

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The findings and analysis of this dissertation support the research hypothesis. A methodological and detailed decomposition of selected crew race physical criteria can produce performance parameters useful in modeling situational performance and evaluating optimal strategies. This research successfully answered most of the questions that were formulated to address the research hypothesis. For some questions, this research provided significant data to support further analysis and to parameterize decision-support models to be formulated by future researchers.

1. Can video data be mined as a valuable source of crew race performance data? This research demonstrated the technical feasibility of using video race records to mine crew race performance data at a high level of precision. Race positioning and stroke rates can be analyzed and illustrated in great detail (thousands of observations) with photo-finish precision (30 frames per second).
2. Can drives be statistically analyzed and graphically displayed? Detailed data mined from video records enables the individual drives crews make on each other to be conceptually modeled, graphically visualized, and analyzed. Studying the five position duels for each race seems particularly meaningful, even though two of five of these duels are not medals contests.
3. When are the winning drives made in races? For the 25 position duels studied, decisive drives are observed throughout the 2000-meter race course.

4. How well does the timing of drives correspond to 500-meter splits? The timing of both decisive and challenge drives does not appear to have a relationship to the 500-meter markers.
5. Do crews vary their stroke rates when taking a drive? Stroke rate differentials between crews in a duel are observed to change slightly in some cases to coincide with a drive. However, this was not systematically studied in this research, so a general pattern cannot be concluded.
6. How often do winning crews pull steadily away from the other contenders for the entire length of a race? 32% of decisive drives occur at the race start as these crews are able to take the lead at the very beginning of the race and row a holding race from that point forward.
7. Do crews tactically respond to the challenge of a crew driving on them? The generic drive model defines a “finishing segment” where the eventual winning crew in a duel responds to the challenge drive segment of their opponent. This type of drive response is observed in many races.
8. Do crews hold back and adopt a conservative strategy when a win seems assured? The generic drive model defines a “holding segment” where the eventual winning crew in a duel reaches a holding point in the race where their rate of gain shows a deceleration. This has the appearance of sitting on their lead, but the data cannot be used to explain why this occurred.

9. Are under-stroking crews more likely to make a drive late in a race? Examples of this are seen in the duels studied, but this hypothesis was not systematically studied in this research. Useful data was generated that could lead to future research on this topic.
10. Do crews “save up” their energy just before taking a Big-10 or sprint? Some examples are seen of this in the data, but this was not systematically studied. Furthermore, the motivation and rationale for such pauses cannot be determined.
11. How much different do crews perform during race starts and race ending sprints? The stroke rate data obtained and illustrated in this research clearly shows major differences in stroke rates during racing starts and closing sprints. Future research could explore this detailed data for its overall patterns.
12. Can losing crews be broken, resulting in a fade or total collapse late in the race? Of the 30 crews studied in these 5 races, there were a couple of crews that dramatically slowed in the last 500 meters of the race. The cause for these “collapses” is not known because the crews were out of camera view as they fell behind late in the race.
13. What factors influence the probability of coming from behind to win? Three factors were observed and measured in the data: distance trailing (seconds behind), position along the course, and whether the trailing crew was making a drive on the leader.
14. Is there a practical limit to the amount of distance a trailing crew can hope to make up? Preliminary analysis of drive patterns suggests that at the highest levels of world championship competition, small leads of less than two seconds can be decisive. Winning crews in a duel rarely spot more than a 2-second margin before executing a decisive drive to take the lead for good. Losing crews seem generally unable to spot

a winning crew more than a 1-second lead (especially late in the race) before their challenge drives prove ineffective. A 3-second lead seems to be an overwhelming advantage.

15. Under what circumstances would a crew's optimal strategy shift from trying to catch the crews in front of them, to trying to hold off the crews behind them. After spotting their opponent a narrow lead of less than 1 second, the trailing crew can be expected to come from behind to win 38% of the time. If a crew can initiate a drive while losing closely, they can improve this come-from-behind probability to 60%. Probabilities vary as a function of position along the course. If a probabilistically decisive lead is gained by your opponent, the best strategy may be to shift attention to holding off the crews behind yours.

16. What kinds of race scenarios do coxswains need to be trained in how to respond?

The generic drive model provides a framework for coaching and training coxswains on the contingencies that can occur in a race. The parameterization of a probabilistically decisive lead should help to calibrate a coxswain's judgment as to what race goals are realistically still within the range of feasibility.

Future Research Opportunities

The scope of this research was limited to studying only five world championship races among a total of 30 competing crews. These races included a total of 75 duels of which there were 25 position duels. Expanding the scope of this research to a larger selection of races would improve the reliability of analytical results, and provide greater opportunity for the stratification of results by race class.

Working with such a wealth of detailed race data, new forms of analysis can still be improved upon and developed. For example, the patterns of stroke rate behavior are still unexplored through modeling and analysis. Clearly, detailed stroke rate data is obtainable and can be graphically illustrated as shown in this paper. However, analytical techniques to study any relationship between stroke rate differentials and drive patterns are yet to be developed.

The classic race strategies of rowing a holding race or rowing a come-from-behind even-paced race plan can also be better understood and modeled using detailed race data. Developing a more comprehensive database of drive patterns in actual competition will enable probabilistic models to be more reliably developed to guide crews in how much of a lead they can afford to spot their opponents, and when it is more productive to turn their attention from catching a leader to holding off a challenger.

The results of drive-based research can be visualized using a variety of techniques including graphical analysis, click-through spreadsheet techniques, and VRML 3D immersive replays. Future research opportunities exist to develop new technologies to illustrate and reenact race results including the patterns of drives and the situational behavior associated with achieving a probabilistically decisive lead.

The analysis of race data as illustrated in this research could lead to quantitative race plan profiles being formulated and used to guide crews in their actual race strategy. Rather than strategies based on the general principles of come-from-behind or holding race strategies, coaches could instruct crews and coxswains on when to deviate from their primary race plan and goals to secondary strategies based on known probabilistic predictors of crew race success. Thus, decision-support models could guide real-time race strategy as a function of what constitutes a probabilistically decisive lead and the timing and magnitude of drives possible over the race course. This research provides original, new information that could be built into decision-support models to guide coaches, crews and coxswains in formulating and executing their race plans and contingencies. Parameterized decision-support race plan models have yet to be formulated and built.

Recommendations for Regatta Administration

Based on the practical aspects of performing video research and the perceived benefits of being able to work with improved video source files, a series of suggestions can be made for how race administration and video recording might be improved:

1. Always space courses using 10-meter buoys. This allows analyses to be easily translated into other common multiples such as 50-meters, 100-meters, etc. Although you can also do this with 12.5 meter spacing, the mental math is easier.
2. Buoys between the splits markers should be evenly spaced and synchronized with the splits markers.
3. Replace officials using stop-watches with electronic recording of splits. If splits are not highly accurate, delay the final official splits reporting until after post-race review. Real-time splits during a race may need to be approximate if officials are used, but the final splits should be updated to correct for inaccuracies.
4. Expand splits to 250-meter intervals to add analytical granularity and to isolate starts and sprints.
5. On-board electronic tracking technology exists that enables crews to be tracked with great precision. At present, the rules of competitive rowing prohibit technology from being used in a race that enable the transmission of information to or from crews during a race. Perhaps, these prohibitions should someday be amended to allow regatta officials to use tracking devices that are based on on-board monitoring technology.

6. Ultimately, as monitoring technology evolves, expand split reporting to 10-meter intervals (but not more detailed). Done electronically, 10-meter splits reporting could enable real-time graphical display of drives and relative position graphics during live race broadcast coverage.
7. Until electronic tracking is feasible at 10-meter intervals, camera coverage should be more comprehensive of all crews while minimizing blind spots. Record (and separately publish on the FISA DVDs) an aerial view of the entire race showing all crews throughout the race. This will allow post-race analysts to manually track each crew without any blind spots. Perhaps allow blind spots in coverage of trailing crews that are behind by more than 12 seconds. Adjust the aerial camera lens to zoom into this 12-second range (about 3 lengths of open water behind the leader).
8. If a separate race video recording is not published for analytical purposes, then use split screens for zoom camera work while simultaneously showing the race detail elsewhere on the screen.
9. Decision-support models can be built to include the factors that influence what constitutes a probabilistically decisive lead. When it becomes practical to link these models to real-time race data, the broadcasting of race results could be enhanced with analytical insight about how crews are driving on each other and at what point the lead by the winning crew seems decisive.

Limitations of This Research

Video analysis is very time consuming. Even assisted by a highly automated Race Observation Event Log (ROEL), extracting buoy hits and blade catches requires an average of 24 labor-hours of video data entry per race. Only five races were analyzed (2 men's eights races, 2 women's, and 1 lightweight men's 8's).

Race analysts will always be interested in studying how the gold medal crews achieved their successes – especially against the silver medal crews. To increase the research sample, other duels were studied besides the gold medal duels. With 6 crews in each of these 5 races, 30 separate individual crew performances were recorded. When you further factor in that there are 5 positions being fought over (1st through 5th place), then there are actually 15 separate duels (pairs of crews) racing against each other within each single race. The 75 total duels studied in this research are representative of the average caliber of competition that can be expected from crews that are capable of earning their spot into a world or Olympic championship final. From these 75 total duels, there were 25 highly competitive “position duels” that ultimately determined the exact order of finish in each race.

With only five races studied, this research could not be meaningfully stratified between male and female competitions, and between lightweight and heavyweight competitions. The somewhat slower times for lightweight competitions could affect race physiology, and therefore possibly affect the patterns of drives and probabilities of coming from behind in a race. Differences by gender also affect average race times with a potential similar impact on race physiology. It remains unexplored as to whether any of the other factors of crew race performance including strategy and tactics might be significantly affected by gender.

The races studied were all 8-oared championship finals events – generally regarded as the premier competitions. However, world and Olympic championships also have competitions in smaller boat classes including singles, pairs, and fours – sometimes with rowers using one oar (sweep events) and sometimes with two oars per rower (sculling events). The smaller boats may or may not be coxed events – in which case one of the rowers must assume the decision-making role of the coxswain. It remains unexplored as to how these research findings for 8-oared competition would generalize to small boat events.

This dissertation also introduced a generalized conceptual model of crew race performance (Figure 2-1). This model provided a framework for organizing a large and diverse body of secondary research into a coherent literature review (Chapter Two.) However, no further research was done in this dissertation to validate this as a conceptual model. The model also remains untested as a practical tool for race performance analysis. For example, this model could theoretically be used by race analysts (including coaches) to categorize and interpret the performance differences between two crews in the same race or to interpret the performance differences of the same crew in two different races.

Significance of the Study

This research raises the standard by which world and Olympic rowing competitions can be studied. Detailed modeling and analysis of Olympic and world championship eights races should prove to be of keen interest to coaches, competitors and rowing researchers, especially when performed at a level of data granularity 1000 times more detailed than studied before in any of the literature.

This research demonstrates the value of more precise race tracking technology. This research demonstrated the feasibility and defined some of the practical limitations of mining video race records for their information value. Given the labor-intensiveness of mining video records (even when supported by customized software), the demand should increase for more automated electronic techniques for tracking races at a high level of granular detail. As new technologies become practical for detailed race tracking, the analytical methods piloted in this dissertation should serve as prototypes for what to do with such data.

This research also provides new insights into drive-based strategy and the tactics most closely associated with race performance success. The pattern of drives illustrated in this research quantifies for the first time ever the frequencies, closing rates and the amount of time winning crews are able to make up in a world championship eights race (decisive drives). This research also quantifies the locations and patterns of losing drives in a race (challenge drives).

Besides demonstrating the value of additional race detail, this research has resulted in an original database of detailed results for the 8's competition from some major international regattas of recent years. This database lays the foundation for a variety of future research studies, especially as more race results are added over time.

This research has also demonstrated the value of applying industrial engineering techniques to studying athletic races – crew races in particular, but which can be generalized to other types of athletic races. Biomechanical, ergonomic and physiological principles are vital components of the 8-Factor Model of Crew Race Performance. The 8-factor model also considers the strategy and tactical aspects of race performance – for which this research has demonstrated the practical value of industrial engineering modeling techniques and decision-support analytics.

*The key to executing a come-from-behind race strategy is to initiate a decisive drive.
The key to executing a holding race strategy is to limit your opponents to challenge drives.*

Jeff Cornett

APPENDIX A: PATTERNS OF BLIND SPOT FREQUENCIES

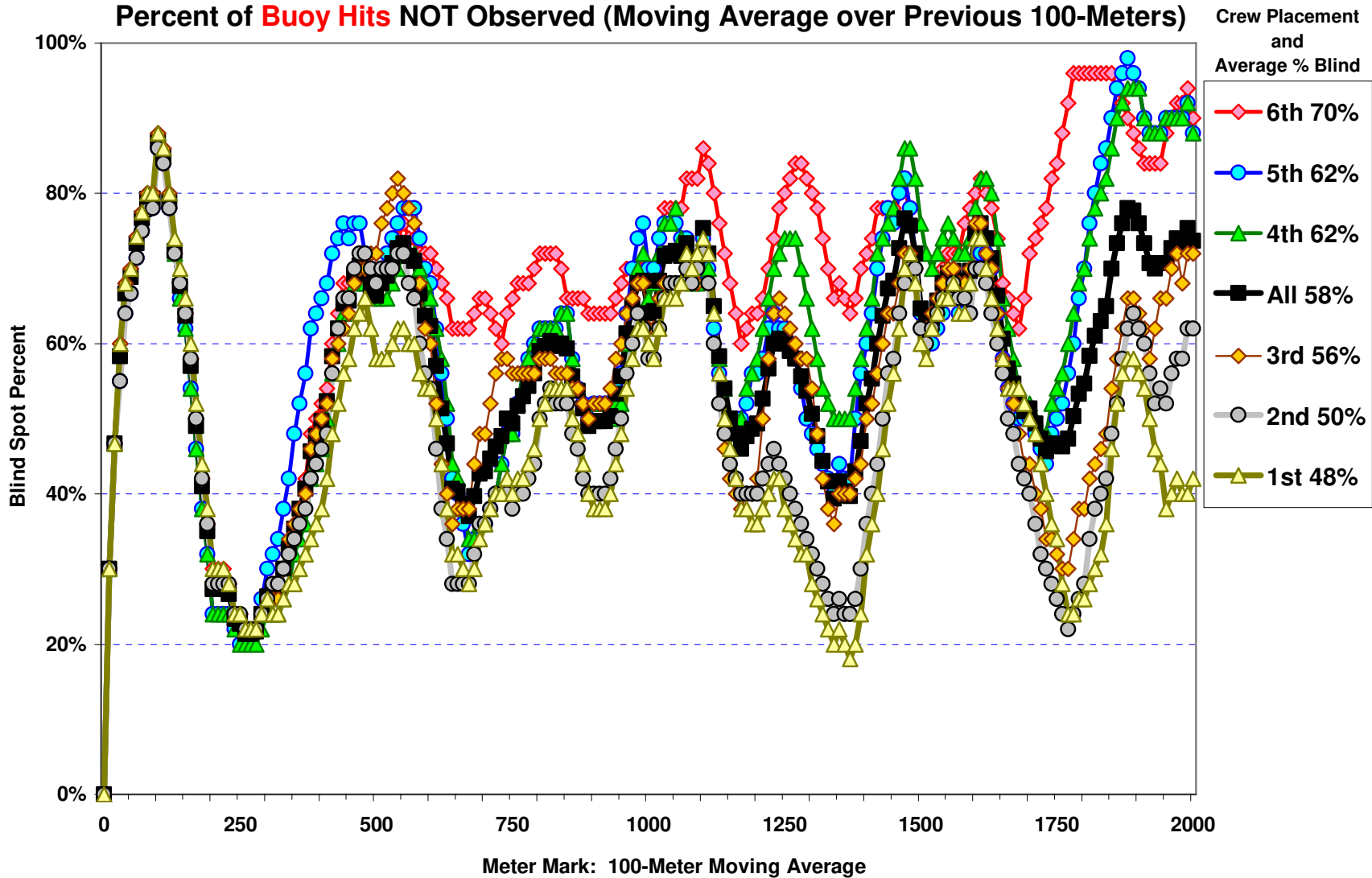
Crews may not always be visible on screen during a video race replay. This may be due creative camera angles such as during a close-up of a single crew. It may also be due to the fact that a trailing crew may have dropped back to the point where they can no longer be seen. A crew may also be visible on screen, but the distance from the crew and the angle of view may prevent a reliable observation to be made as to when the crew reaches a buoy marker or when their oars exactly make a catch. During these “blind spots” where a crew is not sufficiently visible to record clear observations, the location on the course (buoy hits) and stroke rate (oar catches) can still be algebraically extrapolated from before and after observations of that crew.

The following graphics show the average frequency of blind spots for the five races studied. The first graph shows the percentages of buoy hits not observed. The second graph shows the percentage of catches not observed. A high blind spot percentage (approaching 100%) means that at this point in the race, crews usually were not visible in the video coverage.

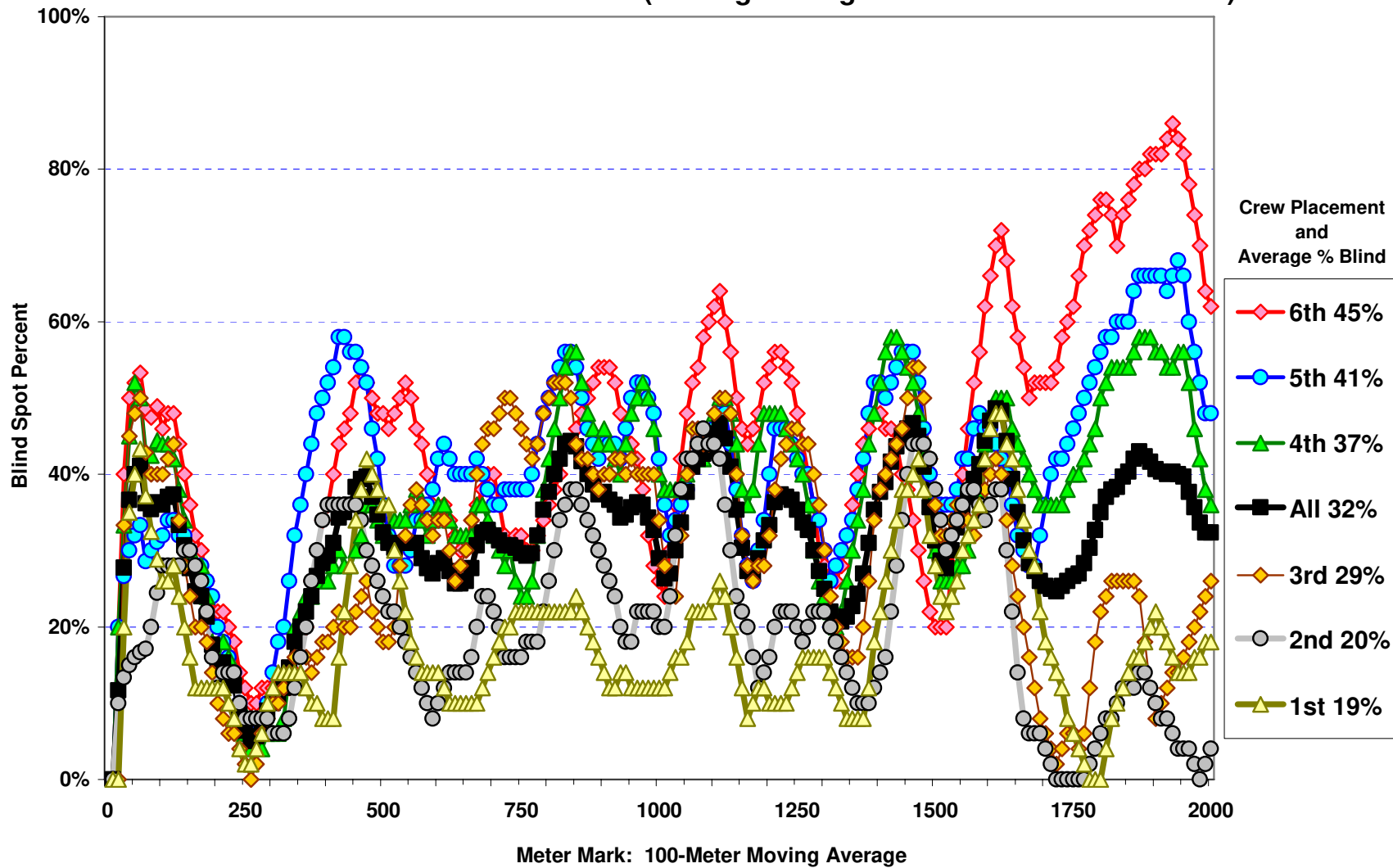
Oar catches are easier to observe in videos. One need only observe a single oar to observe a catch. Catches can also be reliably observed from observing the momentum shifts and hand movements of the oarsmen even when their oars cannot be seen.

Results are reported separately for each crew placement (from 1st through 6th place). Camera coverage tends to follow the race leaders, so crews in the lead tend to have blind spots less often.

Course Position Blind Spot Rates (All 5 Races Combined)
Percent of Buoy Hits NOT Observed (Moving Average over Previous 100-Meters)



Stroke Rate Blind Spot Rates (All 5 Races Combined)
Percent of **Catches** NOT Observed (Moving Average over Previous 100-Meters)

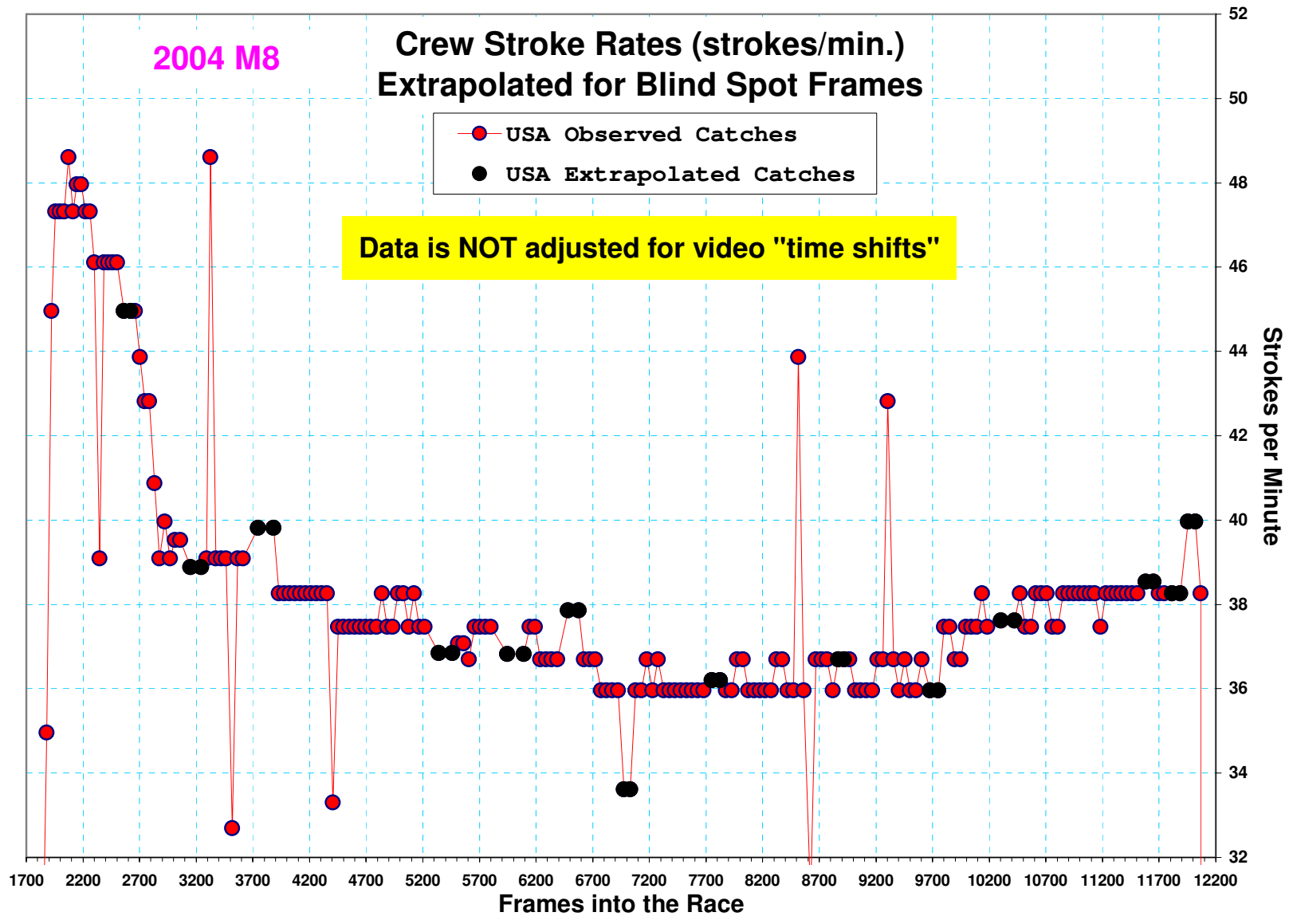


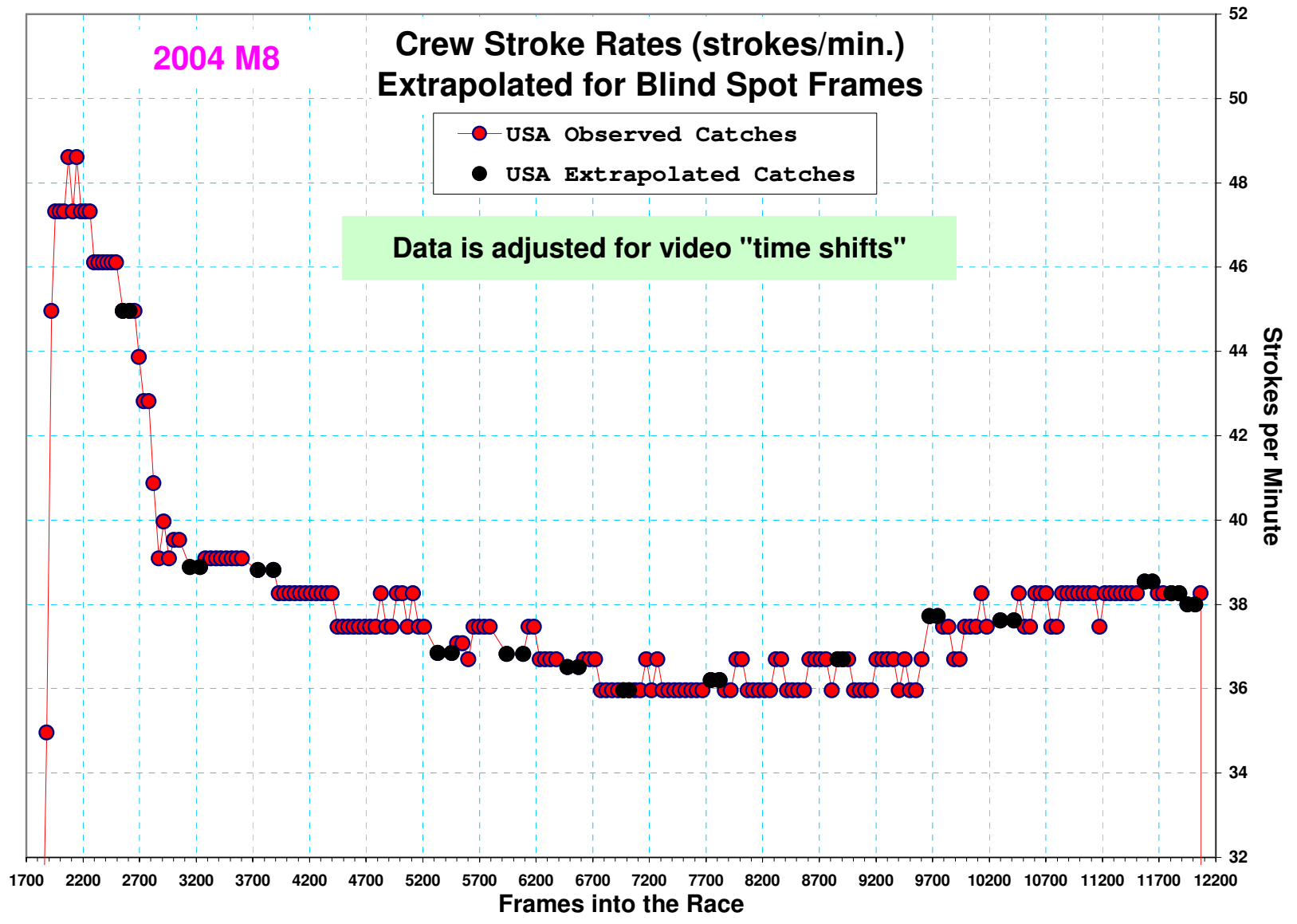
APPENDIX B: STROKE RATE CORRECTIONS FOR VIDEO TIME SHIFTS

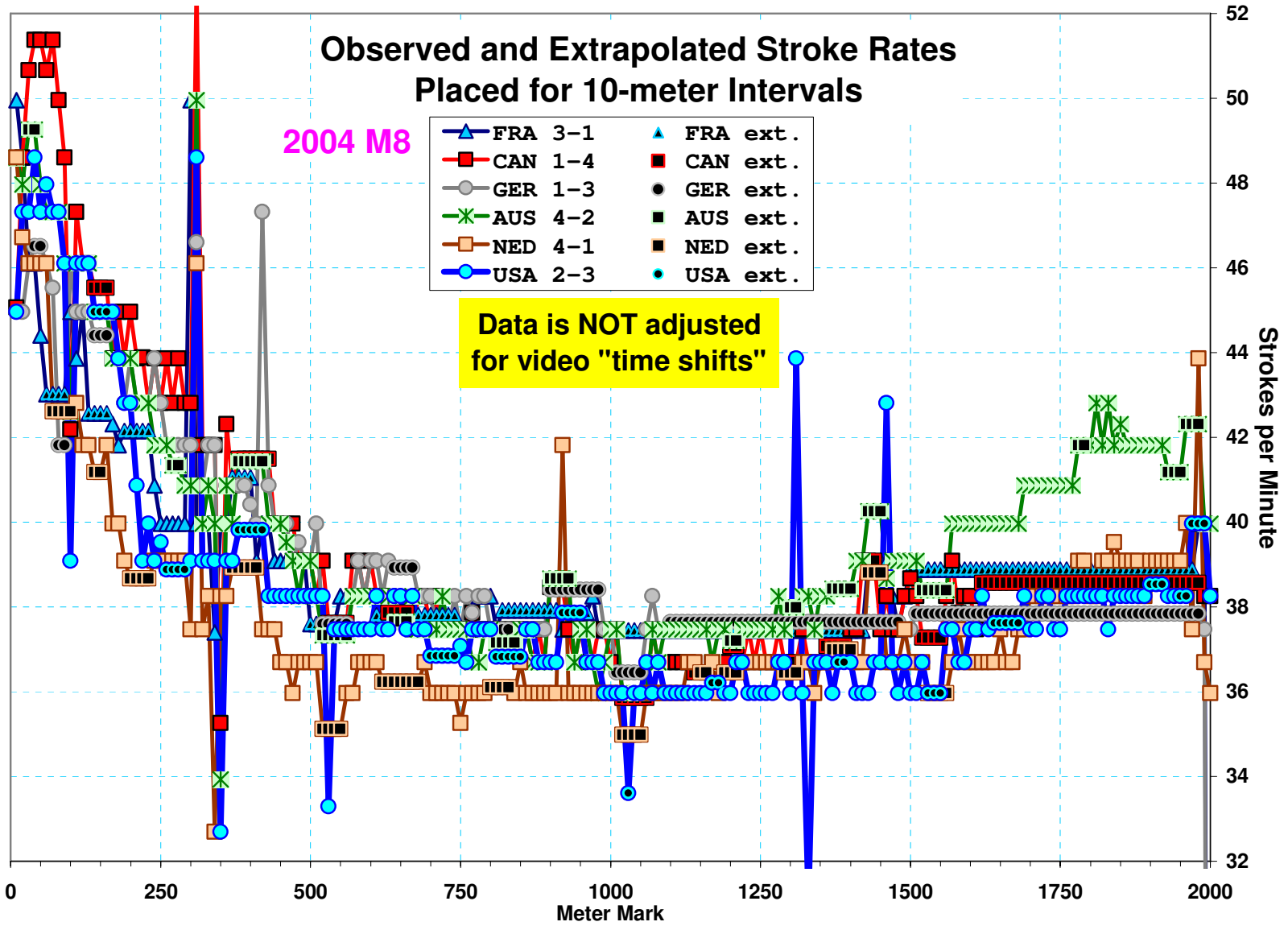
When camera views change, there may be differences in transmission times from the different cameras to the broadcast center. This can result in slight gaps in video coverage or slight overlaps in video coverage. These timing imperfections are not detectable to a person viewing the race, but they can result in major discrepancies (up to half a second) when measuring race events at 30 frames per second precision.

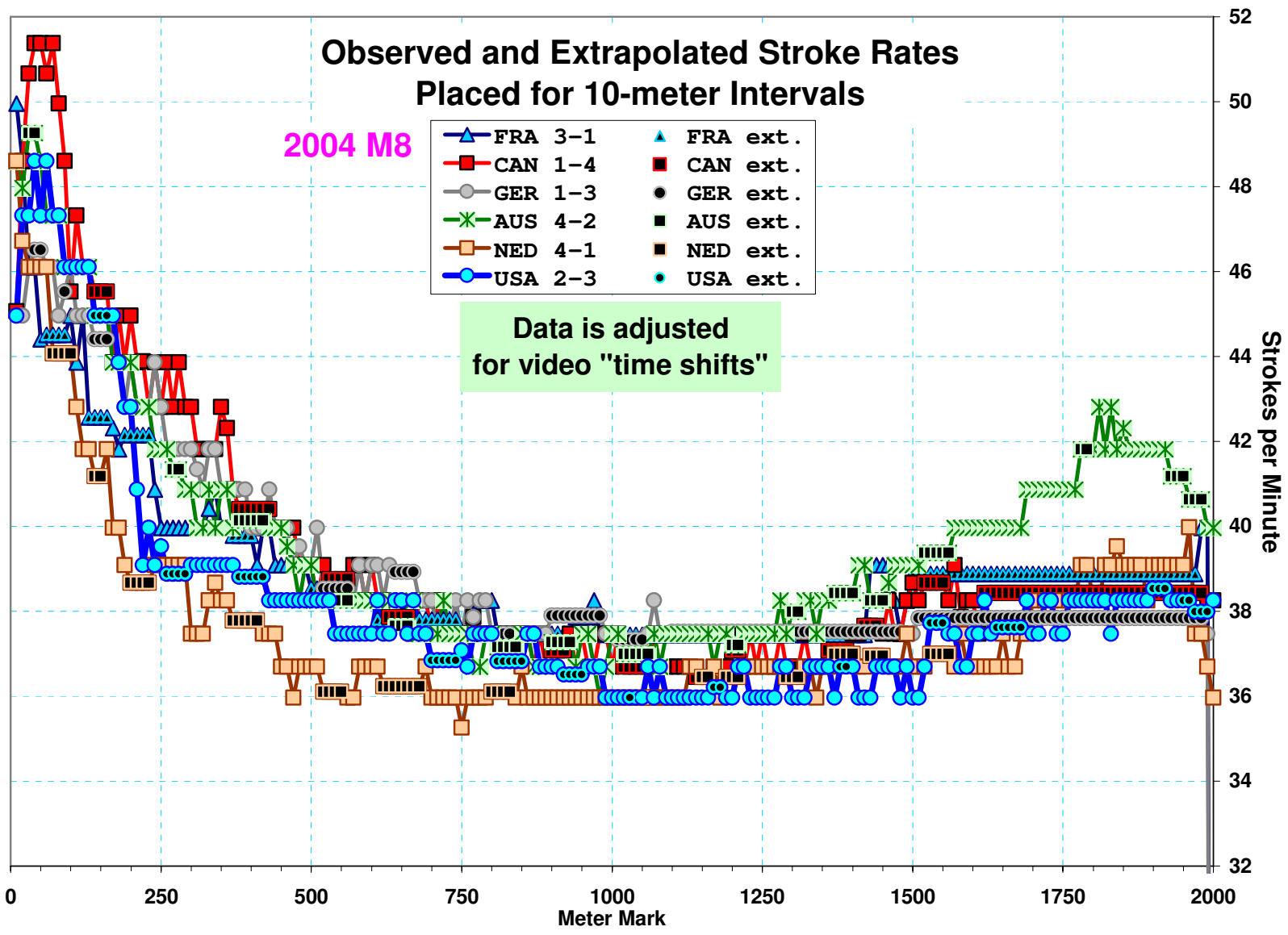
Such defects can create obvious major distortions in stroke rates, and may have also impact other race statistics in less obvious ways. Since stroke rates are usually very regular in pacing, the timing from catch to catch before and after a camera shift can be used to accurately estimate the distortion during a camera shift.

EEVA software is designed to adjust for these camera view transmission defects. The following exhibits illustrate the before and after effects of adjusting for these defects. The first pair of graphs shows adjustments made to smooth the stroke rates for a single crew as camera angles shift. These adjustments, if done accurately, will have the effect of correcting the stroke rates for all the other crews – as illustrated in the second pair of stroke rate graphs.









APPENDIX C: DRIVE PARAMETER DATA – 15 DUELS PER RACE

In a 6-boat race, there are 15 unique combinations of pair duels. A wide range of performance statistics can be calculated for the various combinations of crews dueling within a race. The generic drive model can be used as a means of segmenting performance statistics over the various portions of each duel – as illustrated in the following table for the 2004 W8 Olympic finals.

The holding point (**H**) and challenge point (**C**) are subjectively identified by the race analyst. The other points of the generic drive model (**W**, **P**, and **B**) are automatically identified by the EEVA software. From these points, the software algebraically computes all of the other race performance parameters – including differential stroke rates and the closing rate of crews on each other (measured in seconds gained or lost per meter traveled).

Class:		2004 W8	2004 W8	2004 W8	2004 W8	2004 W8	2004 W8	2004 W8	2004 W8	2004 W8	2004 W8	2004 W8	2004 W8	2004 W8	2004 W8	2004 W8	2004 W8	2004 W8
Duel Teams:		ROM 1 v2 USA	ROM 1 v3 NED	ROM 1 v4 CHN	ROM 1 v5 GER	ROM 1 v6 AUS	USA 2 v3 NED	USA 2 v4 CHN	USA 2 v5 GER	USA 2 v6 AUS	NED 3 v4 CHN	NED 3 v5 GER	NED 3 v6 AUS	CHN 4 v5 GER	CHN 4 v6 AUS	GER 5 v6 AUS		
Duel Number:		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		
Duel Winner:		ROM 1 v2-6	ROM 1 v2-6	ROM 1 v2-6	ROM 1 v2-6	ROM 1 v2-6	USA 2 v3-6	USA 2 v3-6	USA 2 v3-6	USA 2 v3-6	NED 3 v4-6	NED 3 v4-6	NED 3 v4-6	CHN 4 v5-6	CHN 4 v5-6	GER 5 v6-6		
Teams2		1 v2 USA	1 v3 NED	1 v4 CHN	1 v5 GER	1 v6 AUS	2 v3 NED	2 v4 CHN	2 v5 GER	2 v6 AUS	3 v4 CHN	3 v5 GER	3 v6 AUS	4 v5 GER	4 v6 AUS	5 v6 AUS		
Starting Margin (0 sec)	Sec_Start	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Worst Margin (sec)	Sec_Worst	-0.29	0.00	-0.09	0.00	0.00	0.00	-0.14	-0.02	-0.02	-0.80	-0.70	-1.70	-0.37	-1.23	-1.35		
Passing Margin (0 sec)	Sec_Pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Holding Margin (sec)	Sec_Hold	1.00	1.50	1.35	3.07	3.70	1.66	1.47	1.85	2.54	1.13	0.95	1.67	0.26	0.60	0.73		
Best Margin After Pass (sec)	Sec_Best	1.99	2.39	4.00	4.30	13.95	1.93	2.16	2.44	12.08	1.84	2.14	11.78	0.30	9.94	9.64		
Challenge Margin (sec)	Sec_Chall	1.88	2.29	4.00	4.30	13.95	1.05	2.14	2.44	12.08	1.84	2.14	11.78	0.30	9.94	9.64		
Finishing Margin (sec)	Sec_Finish	1.87	2.17	4.00	4.30	13.95	0.30	2.14	2.44	12.08	1.84	2.14	11.78	0.30	9.94	9.64		
Starting Point (=0)	Point_Start	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Worst Margin Point	Point_Worst	370	0	50	0	0	0	40	40	40	1120	570	870	1650	710	980		
Passing Point	Point_Pass	1250	0	190	30	0	0	80	50	50	1430	1230	1440	1860	1700	1630		
Holding Point	Point_Hold	1600	500	660	1800	1750	470	660	1160	1750	1650	1820	1750	1940	1750	1750		
Best Margin After Pass Point	Point_Best	1930	1890	1990	2000	2000	1160	1990	1990	2000	2000	2000	2000	2000	2000	2000		
Challenge Point	Point_Chall	1970	1950	2000	2000	2000	1470	2000	2000	2000	2000	2000	2000	2000	2000	2000		
Finishing Point (=2000)	Point_Finish	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000		
Spotting Rate (sec/m)	Rate_Worst	-0.0008		-0.0019				-0.0036	-0.0005	-0.0005	-0.0007	-0.0012	-0.0020	-0.0002	-0.0017	-0.0014		
Closing Rate (sec/m)	Rate_Pass	0.0003		0.0007	0.0000			0.0036	0.0022	0.0021	0.0026	0.0011	0.0030	0.0017	0.0012	0.0021		
Passing Rate (sec/m)	Rate_Hold	0.0029	0.0030	0.0029	0.0017	0.0021	0.0035	0.0025	0.0017	0.0015	0.0052	0.0016	0.0054	0.0032	0.0120	0.0061		
Holding Rate (sec/m)	Rate_Best	0.0030	0.0006	0.0020	0.0062	0.0410	0.0004	0.0005	0.0007	0.0382	0.0020	0.0066	0.0404	0.0007	0.0374	0.0356		
Challenge Rate (sec/m)	Rate_Chall	-0.0027	-0.0016	0.0000			-0.0028	-0.0027	0.0000									
Finishing Rate (sec/m)	Rate_Finish	-0.0004	-0.0024				-0.0014											
Drive Profile	Profile	WPBHC	HBC	WPBH	PH	H	HBC	WPBH	WPBH	WPH	WPH	WPH	WPH	WPH	WPH	WPH		
Average Stroke Rate Differential (SRD)																		
Spotting SRD (strokes/min)	SRD_Worst	1.7		0.7				-1.5	-1.4	-1.7	-0.6	-2.8	-3.2	-2.1	-2.7	-0.5		
Closing SRD (strokes/min)	SRD_Pass	0.2		2.0	1.4			-0.5	-0.5	-0.5	-0.4	-2.6	-2.7	0.7	-2.0	0.0		
Passing SRD (strokes/min)	SRD_Hold	0.1	2.6	2.1	-0.3	-0.5	1.1	1.1	-1.0	-0.9	-0.3	-2.4	-1.7	2.7	1.6	1.1		
Holding SRD (strokes/min)	SRD_Best	0.1	2.2	0.9	0.9	3.2	2.3	0.8	-0.1	3.2	-3.4	-0.9	1.1	4.9	5.0	2.4		
Challenge SRD (strokes/min)	SRD_Chall	-0.1	1.9	-3.9			1.8	-2.0	2.7									
Finishing SRD (strokes/min)	SRD_Finish	-0.6	1.8				2.1											
0-250	SRD_0-250	1.9	2.6	2.0	0.3	0.2	0.7	0.2	-1.6	-1.7	-0.5	-2.3	-2.4	-1.7	-1.9	-0.1		
250-500	SRD_250-500	1.0	2.7	2.2	-0.5	-1.1	1.7	1.2	-1.5	-2.1	-0.5	-3.2	-3.8	-2.6	-3.3	-0.6		
500-750	SRD_500-750	0.2	2.3	1.7	-0.8	-1.4	2.1	1.5	-1.0	-1.6	-0.7	-3.1	-3.7	-2.5	-3.0	-0.6		
750-1000	SRD_750-1000	0.1	2.2	1.7	-0.1	-0.6	2.0	1.6	-0.2	-0.8	-0.5	-2.3	-2.8	-1.8	-2.4	-0.6		
1000-1250	SRD_1000-1250	-0.1	2.2	1.4	-0.6	-0.5	2.3	1.5	-0.5	-0.5	-0.8	-2.8	-2.8	-2.0	-1.9	0.1		
1250-1500	SRD_1250-1500	0.2	2.0	1.6	-0.3	-0.5	1.7	1.4	-0.5	-0.7	-0.3	-2.3	-2.5	-2.0	-2.2	-0.2		
1500-1750	SRD_1500-1750	0.0	2.3	1.2	-0.1	0.7	2.2	1.1	-0.2	0.7	-1.1	-2.4	-1.6	-1.3	-0.4	0.9		
1750-2000	SRD_1750-2000	0.0	2.1	-1.8	0.8	3.2	2.1	-1.9	0.7	3.2	-4.0	-1.4	1.1	2.6	5.0	2.4		
0-500	SRD_0-500	1.4	2.6	2.1	-0.1	-0.5	1.2	0.7	-1.5	-1.9	-0.5	-2.7	-3.1	-2.2	-2.6	-0.4		
500-1000	SRD_500-1000	0.2	2.3	1.7	-0.4	-1.0	2.1	1.5	-0.6	-1.2	-0.6	-2.7	-3.3	-2.1	-2.7	-0.6		
1000-1500	SRD_1000-1500	0.1	2.1	1.5	-0.5	-0.5	2.0	1.5	-0.5	-0.6	-0.6	-2.5	-2.6	-2.0	-2.1	-0.1		
1500-2000	SRD_1500-2000	0.0	2.2	-0.3	0.3	2.0	2.2	-0.4	0.3	1.9	-2.5	-1.9	-0.2	0.7	2.3	1.6		
0-2000	SRD_0-2000	0.4	2.3	1.2	-0.2	0.0	1.9	0.8	-0.6	-0.4	-1.0	-2.5	-2.3	-1.4	-1.3	0.2		
Decisive Drive Start Point	Point_DD_Start	1170	0				0	40			1120			1650		980		
Decisive Drive End Point	Point_DD_End	1930	500				470	660			1650			1940		1750		
Decisive Drive Start Margin	Sec_DD_Start	-0.10	0.00				0.00	-0.14			-0.80			-0.37		-1.35		
Decisive Drive End Margin	Sec_DD_End	1.99	1.50				1.66	1.47			1.13			0.26		0.73		
Challenge Drive Start Point	Point_CD_Start	40	1220				1160	660			670			1380		270		
Challenge Drive End Point	Point_CD_End	370	1300				2000	920			1120			1650		980		
Challenge Drive Start Margin	Sec_CD_Start	0.09	1.81				1.93	1.47			-0.27			0.58		0.23		
Challenge Drive End Margin	Sec_CD_End	-0.29	1.61				0.30	1.07			-0.80			-0.37		-1.35		
Challenge Total Start Point	Point_CT_Start	40	1220				1160	660			10			1250		270		
Challenge Total End Point	Point_CT_End	370	1300				2000	920			1120			1650		980		
Challenge Total Start Margin	Sec_CT_Start	0.09	1.81				1.93	1.47			0.09			0.66		0.23		
Challenge Total End Margin	Sec_CT_End	-0.29	1.61				0.30	1.07			-0.80			-0.37		-1.35		
Decisive Drive Closed	Closed_DD	2.09	1.50	0.00	0.00	0.00	1.66	1.62	0.00	0.00	1.94	0.00	0.00	0.62	0.00	2.08		
Best - Worst Closed (sec)	Closed_DT	2.28	2.39	4.10	4.30	13.95	1.93	2.30	2.46	12.10	2.64	2.83	13.48	0.67	11.17	10.99		
Challenge Drive Closed	Closed_CD	-0.38	-0.20	0.00	0.00	0.00	-1.63	-0.40	0.00	0.00	-0.53	0.00	0.00	-0.95	0.00	-1.57		
Challenge Total Closed	Closed_CT	-0.38	-0.20	0.00	0.00	0.00	-1.63	-0.40	0.00	0.00	-0.89	0.00	0.00	-1.03	0.00	-1.57		

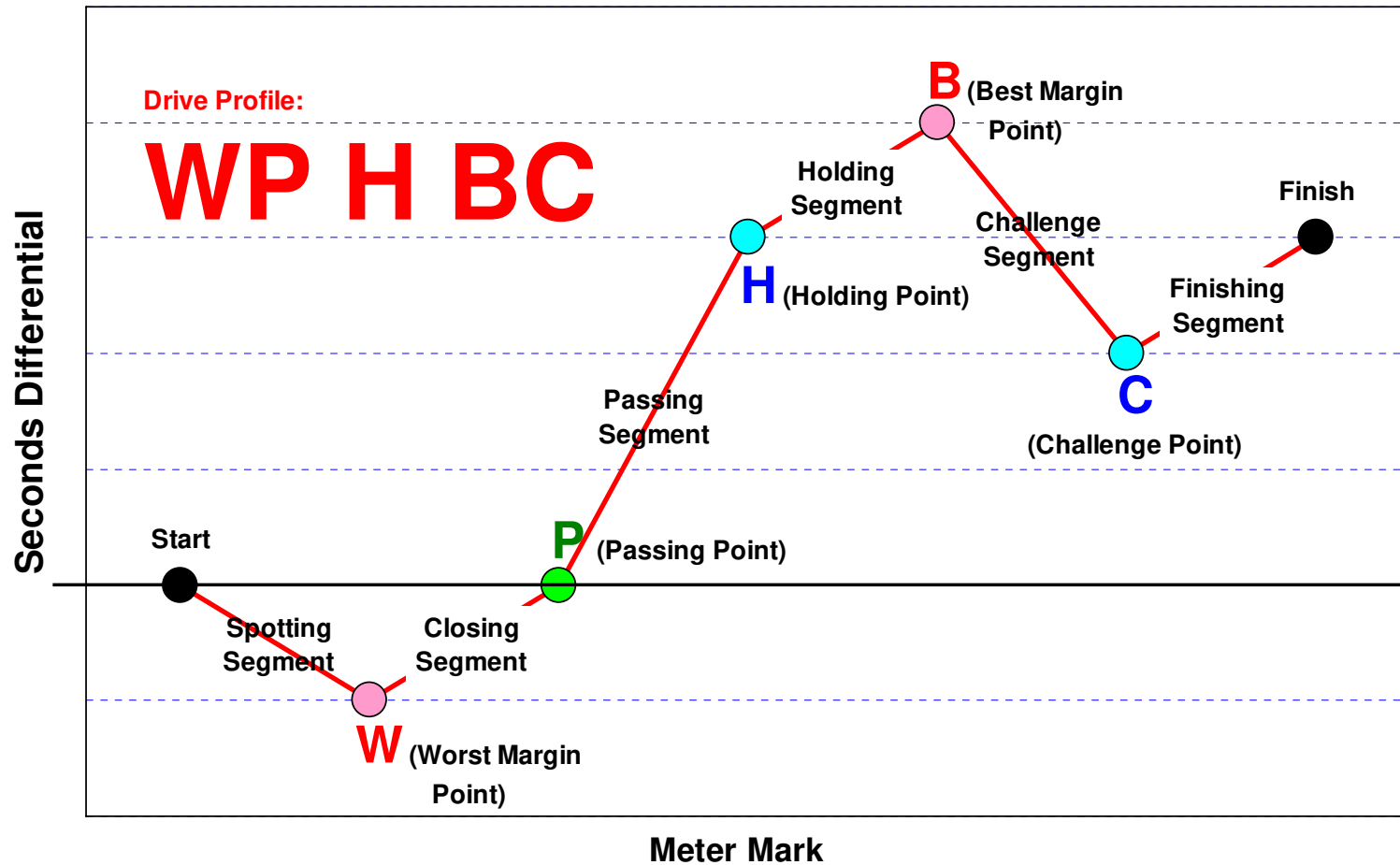
APPENDIX D: GENERIC DRIVE MODELS

The generic drive model of a duel includes six race segments defined by five specific acceleration points (**WPHBC**). When all five of these points can be identified in a duel, the race follows the classic pattern of a come-from-behind race for the eventual race winner followed later in the race by a challenge drive from the eventual losing crew.

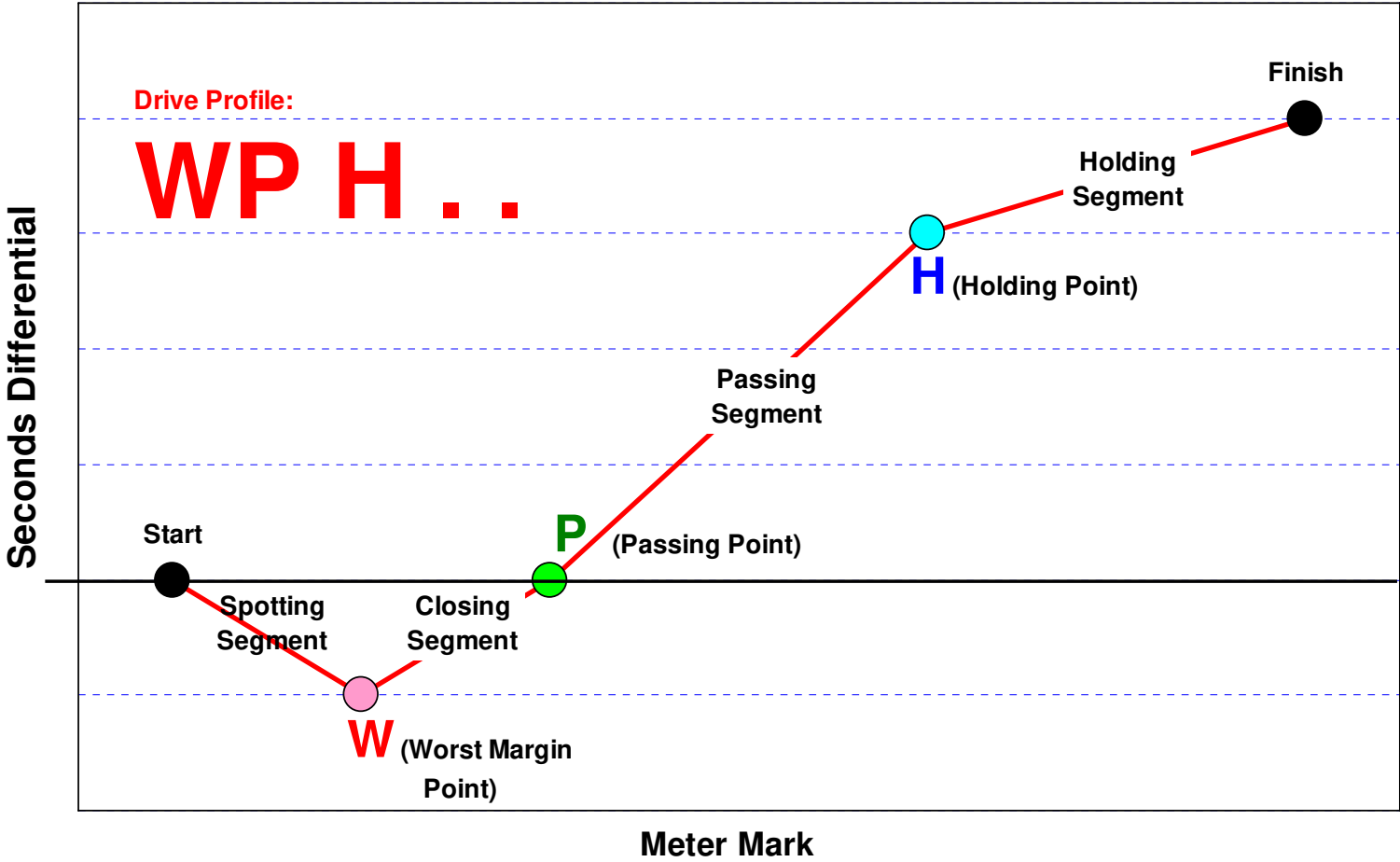
When not all of these acceleration points can be observed, other common drive patterns can be seen. The **WPH** pattern is a come-from-behind race but without a late challenge by the loser of the duel. The **HBC** pattern is a classic holding race where the duel winning crew never does spot the losing crew an early lead.

The following exhibits illustrate these classic drive patterns. Other race drive patterns are possible.

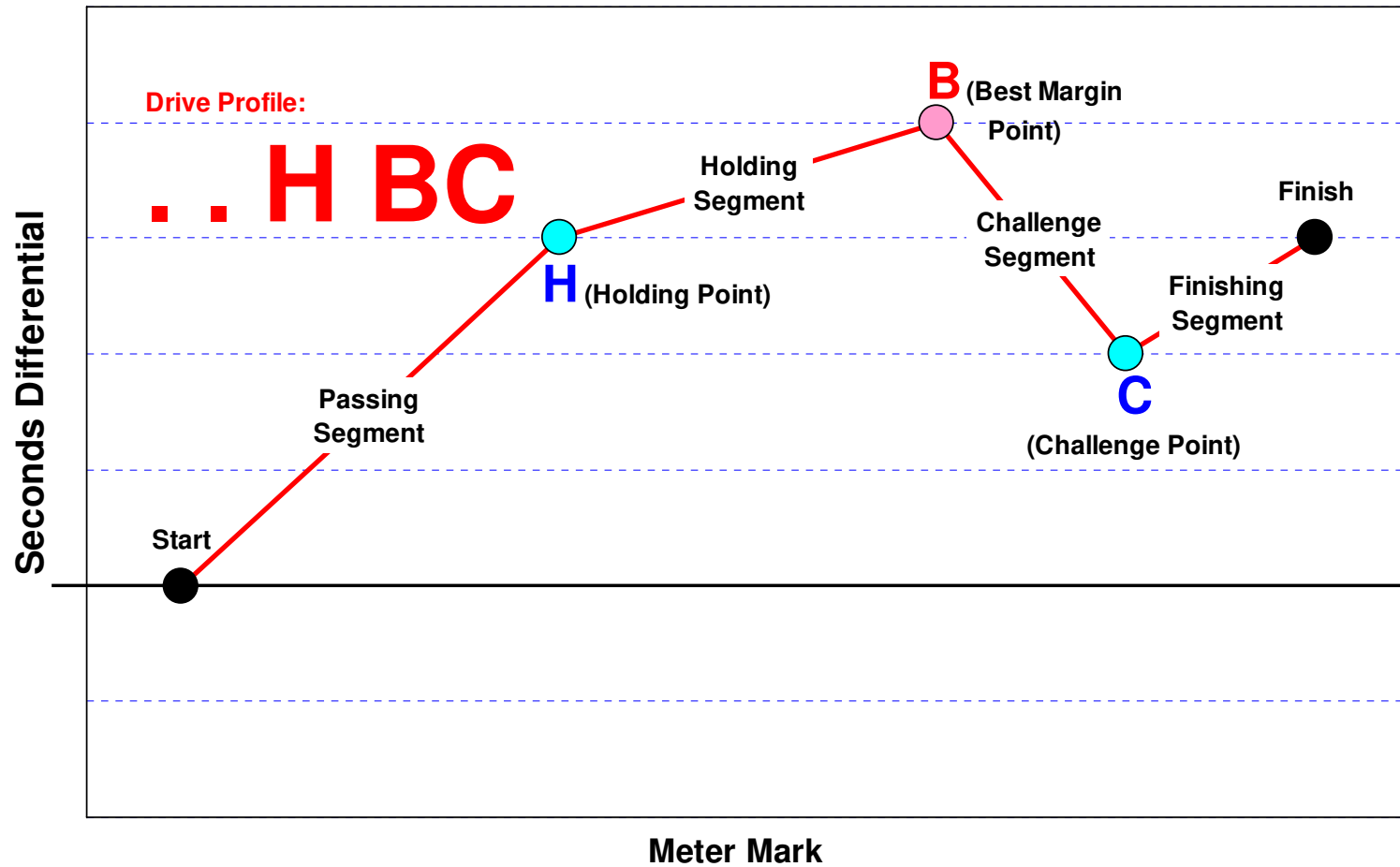
Generic Drive Model of a Duel: “Come-From-Behind” Race with a Challenge



Classic “Come-From-Behind” Race without a Late Race Challenge



Classic “Holding Race” with a Challenge Drive

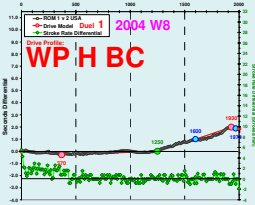
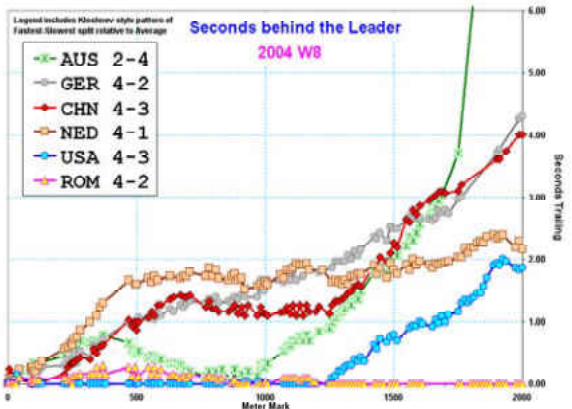
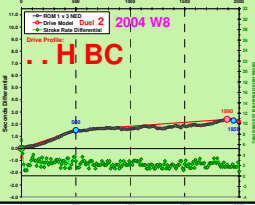
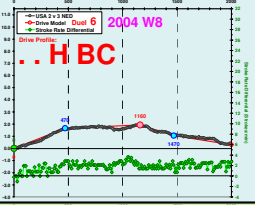
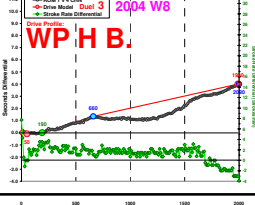
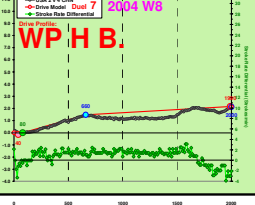
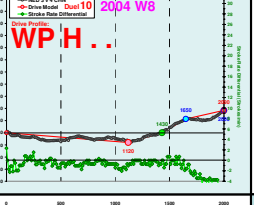
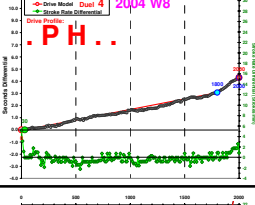
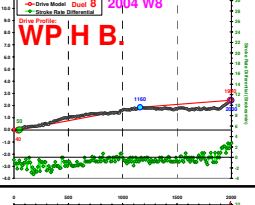
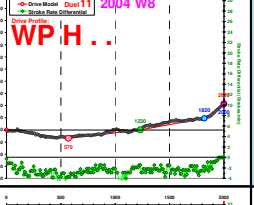
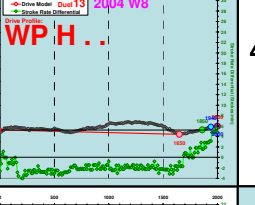
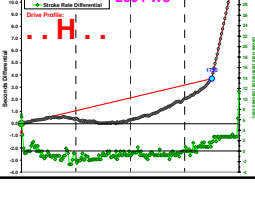
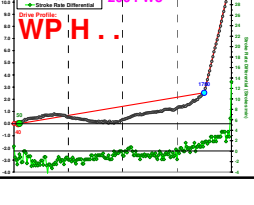
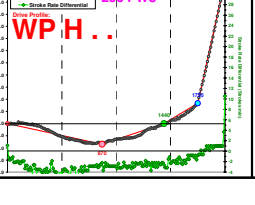
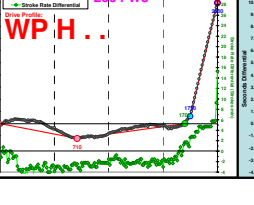
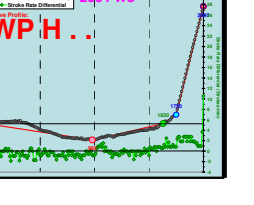


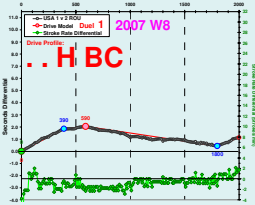
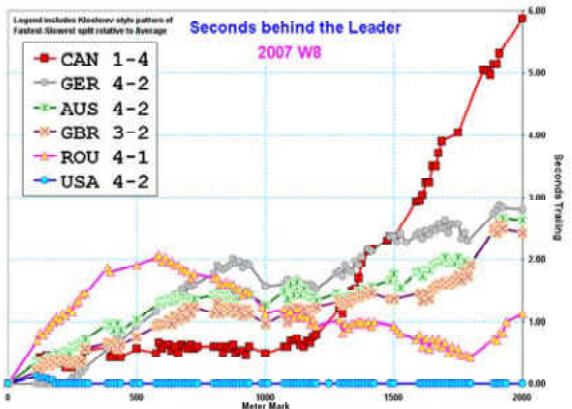
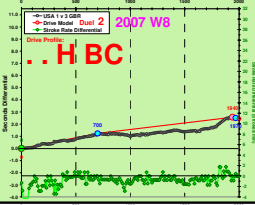
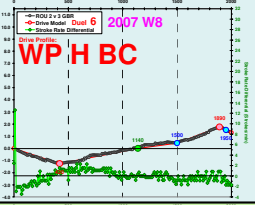
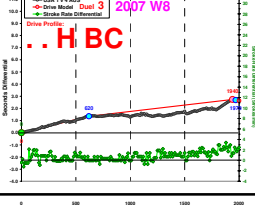
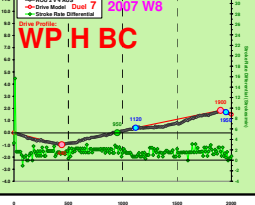
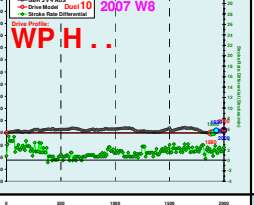
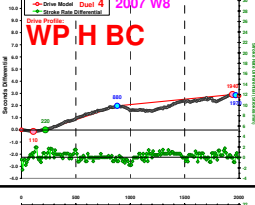
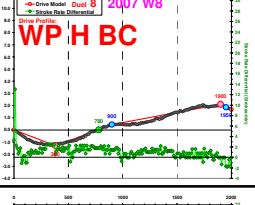
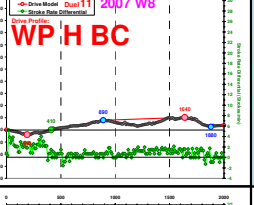
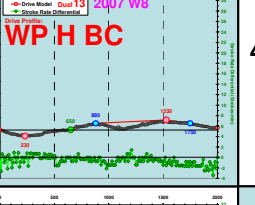
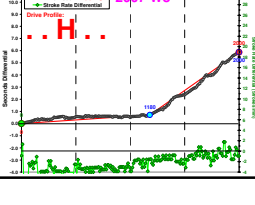
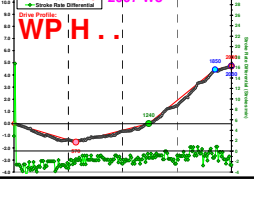
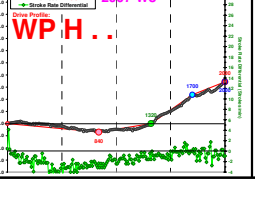
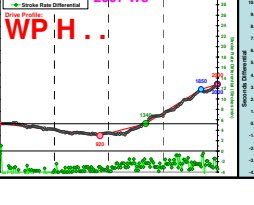
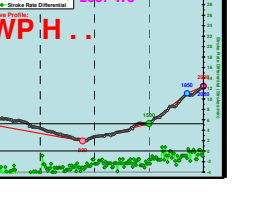
APPENDIX E: 75 RACE-PAIR DUELS FROM 5 CHAMPIONSHIP RACES

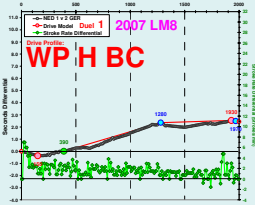
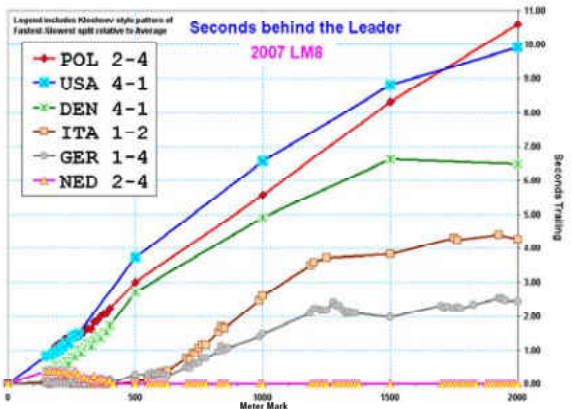
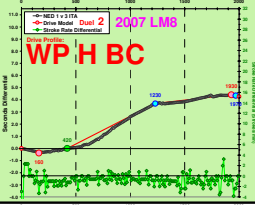
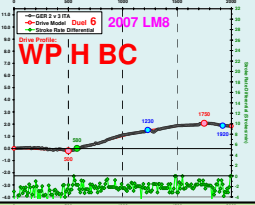
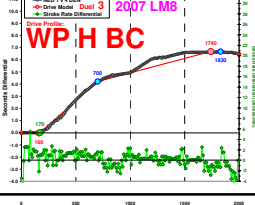
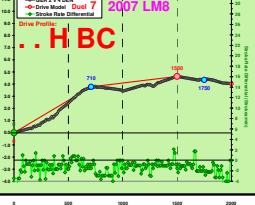
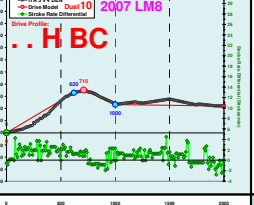
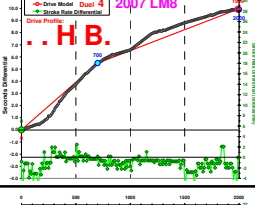
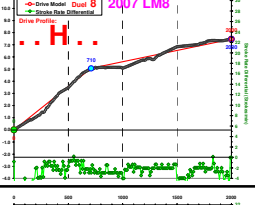
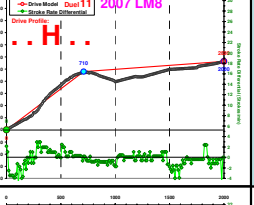
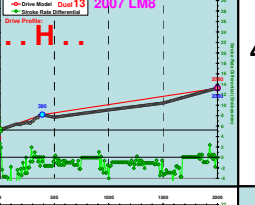
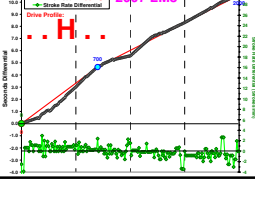
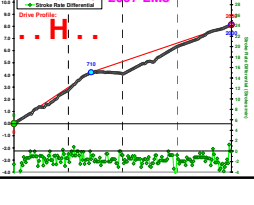
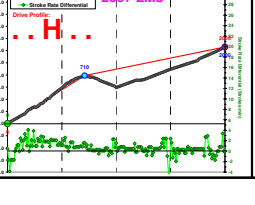
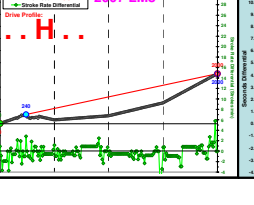
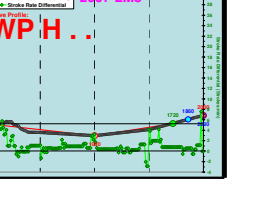
The following exhibits illustrate the generic drive model as applied to each of the 15 race-pair duels in each of the five championship races studied. The 5 duels shaded in blue along the diagonal are defined to be “position duels” since these pairings ultimately determined the order of finish from first to sixth place in each race. The 3 light blue shaded duels are medals competitions for gold, silver and bronze medals.

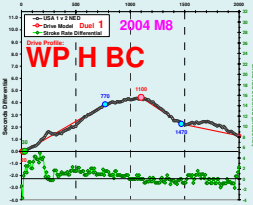
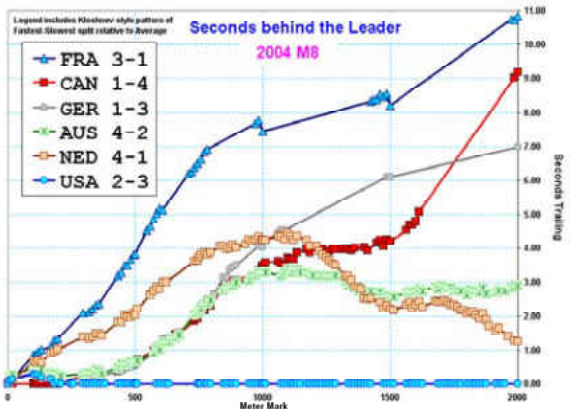
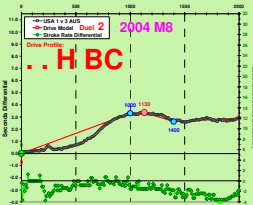
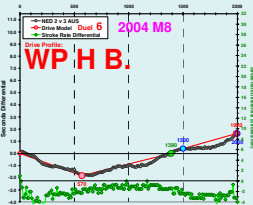
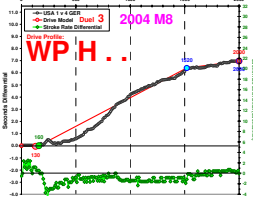
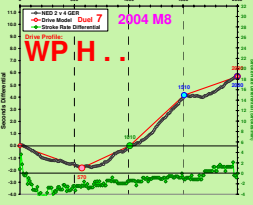
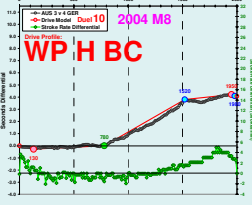
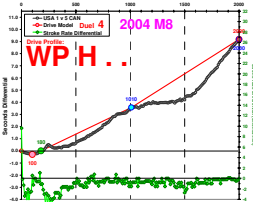
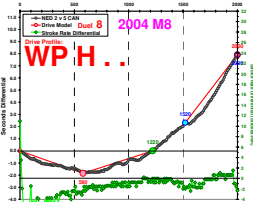
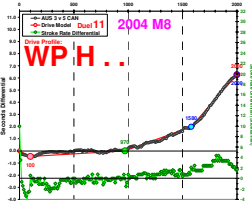
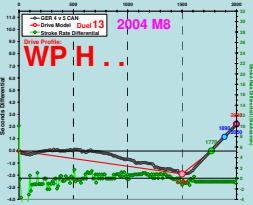
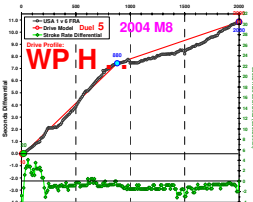
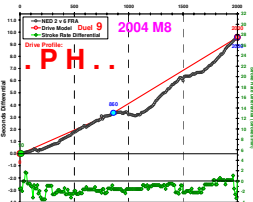
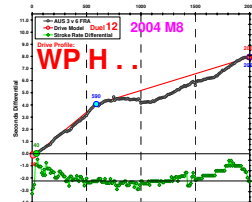
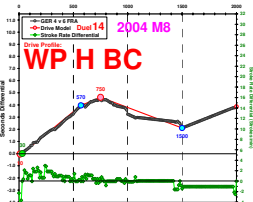
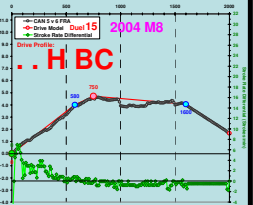
Another taxonomy for how to select the most important duels to study would be to limit consideration to the 5 most critical duels in determining the gold, silver and bronze medals. These medal contender drives are highlighted as the 3 light blue plus the 2 light green duels in each race.

The 8 unshaded duels are the least interesting to consider since these duels were neither the primary determinants for the order of finish (i.e. position duels) nor the most important competitions for the medals (i.e. medal contender duels). They also tend to be the most lopsided competitions.

2004 W8	1st ROM	2nd USA	3rd NED	4th CHN	5th GER
2nd USA	 <p>WP H B C</p>	<p>5 Position Duels are shaded in blue.</p> <p>5 Medal Contender Duels are shaded in green or light blue.</p>			
3rd NED	 <p>. . H B C</p>	 <p>. . H B C</p>			
4th CHN	 <p>WP H B .</p>	 <p>WP H B .</p>	 <p>WP H . .</p>	<p>3 Medal Contender Position Duels are shaded in light blue.</p>	<p>8 Non-Shaded Duels are neither Position Duels nor Medal Contenders.</p>
5th GER	 <p>. P H . .</p>	 <p>WP H B .</p>	 <p>WP H . .</p>	 <p>WP H . .</p>	<p>2 Duels for 4th and 5th place are Position Duels but not Medal Contenders.</p>
6th AUS	 <p>. . H . .</p>	 <p>WP H . .</p>	 <p>WP H . .</p>	 <p>WP H . .</p>	 <p>WP H . .</p>

2007 W8	1st USA	2nd ROU	3rd GBR	4th AUS	5th GER
2nd ROU		5 Position Duels are shaded in blue. 5 Medal Contender Duels are shaded in green or light blue.			
3rd GBR					
4th AUS				3 Medal Contender Position Duels are shaded in light blue.	8 Non-Shaded Duels are neither Position Duels nor Medal Contenders.
5th GER					2 Duels for 4th and 5th place are Position Duels but not Medal Contenders.
6th CAN					

2007 LM8	1st NED	2nd GER	3rd ITA	4th DEN	5th USA
2nd GER		<p>5 Position Duels are shaded in blue.</p> <p>5 Medal Contender Duels are shaded in green or light blue.</p>			
3rd ITA					
4th DEN				<p>3 Medal Contender Position Duels are shaded in light blue.</p>	<p>8 Non-Shaded Duels are neither Position Duels nor Medal Contenders.</p>
5th USA					<p>2 Duels for 4th and 5th place are Position Duels but not Medal Contenders.</p>
6th POL					

2004 M8	1st USA	2nd NED	3rd AUS	4th GER	5th CAN
<p>2nd NED</p>	 <p>WP H BC</p>	<p>5 Position Duels are shaded in blue.</p> <p>5 Medal Contender Duels are shaded in green or light blue.</p>	 <p>Legend includes Kluge's alpha patterns of Fastest Slowest split relative to Average</p> <p>Seconds behind the Leader 2004 M8</p> <ul style="list-style-type: none"> FRA 3-1 CAN 1-4 GER 1-3 AUS 4-2 NED 4-1 USA 2-3 		
<p>3rd AUS</p>	 <p>.. H BC</p>	 <p>WP H B.</p>	<p>3 Medal Contender Position Duels are shaded in light blue.</p> <p>8 Non-Shaded Duels are neither Position Duels nor Medal Contenders.</p>		
<p>4th GER</p>	 <p>WP H ..</p>	 <p>WP H ..</p>	 <p>WP H BC</p>		
<p>5th CAN</p>	 <p>WP H ..</p>	 <p>WP H ..</p>	 <p>WP H ..</p>	 <p>WP H ..</p>	<p>2 Duels for 4th and 5th place are Position Duels but not Medal Contenders.</p>
<p>6th FRA</p>	 <p>WP H ..</p>	 <p>. P H ..</p>	 <p>WP H ..</p>	 <p>WP H BC</p>	 <p>.. H BC</p>

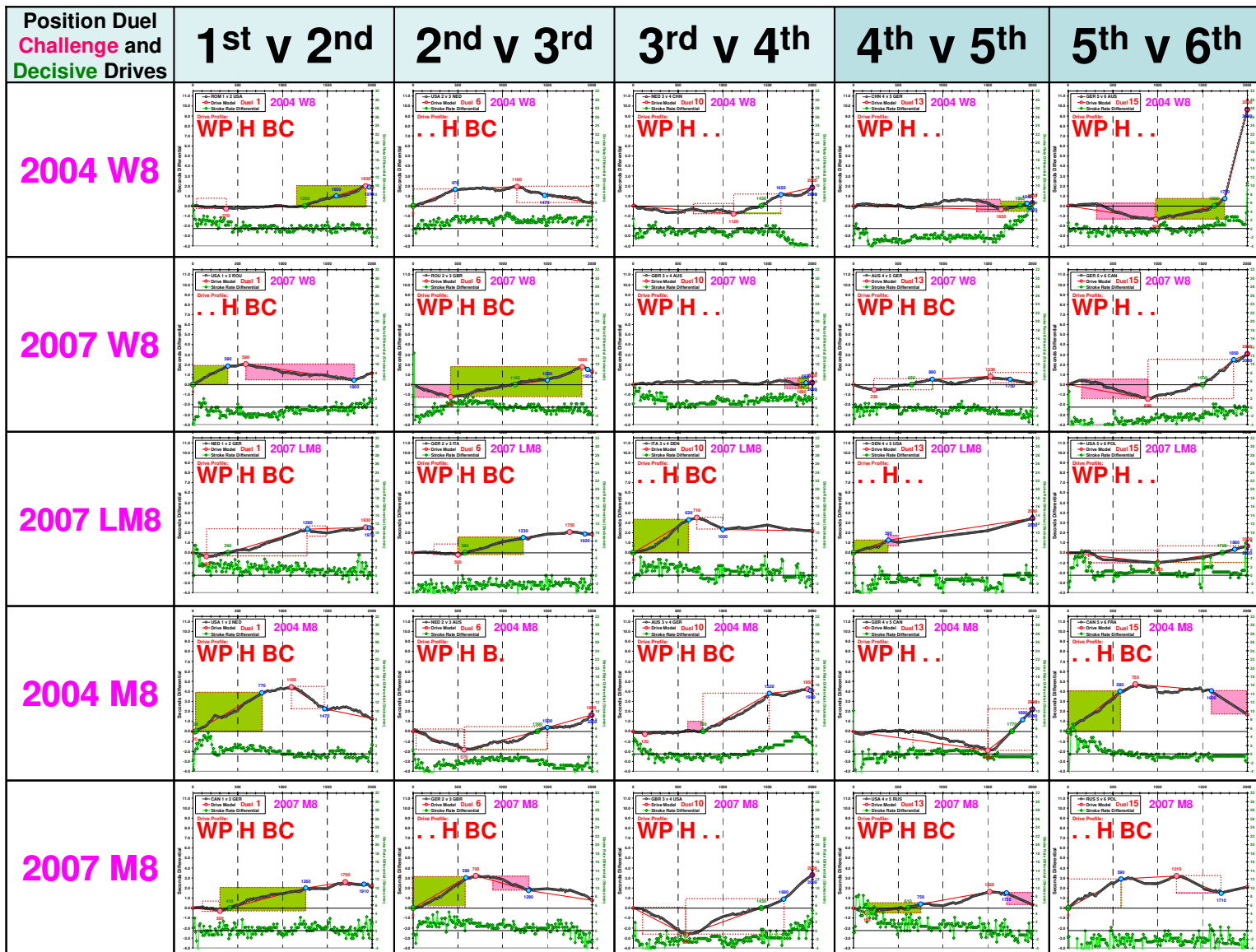
2007 M8	1st CAN	2nd GER	3rd GBR	4th USA	5th RUS
2nd GER		<p>5 Position Duels are shaded in blue.</p> <p>5 Medal Contender Duels are shaded in green or light blue.</p>			
3rd GBR					
4th USA				<p>3 Medal Contender Position Duels are shaded in light blue.</p>	<p>8 Non-Shaded Duels are neither Position Duels nor Medal Contenders.</p>
5th RUS					<p>2 Duels for 4th and 5th place are Position Duels but not Medal Contenders.</p>
6th POL					

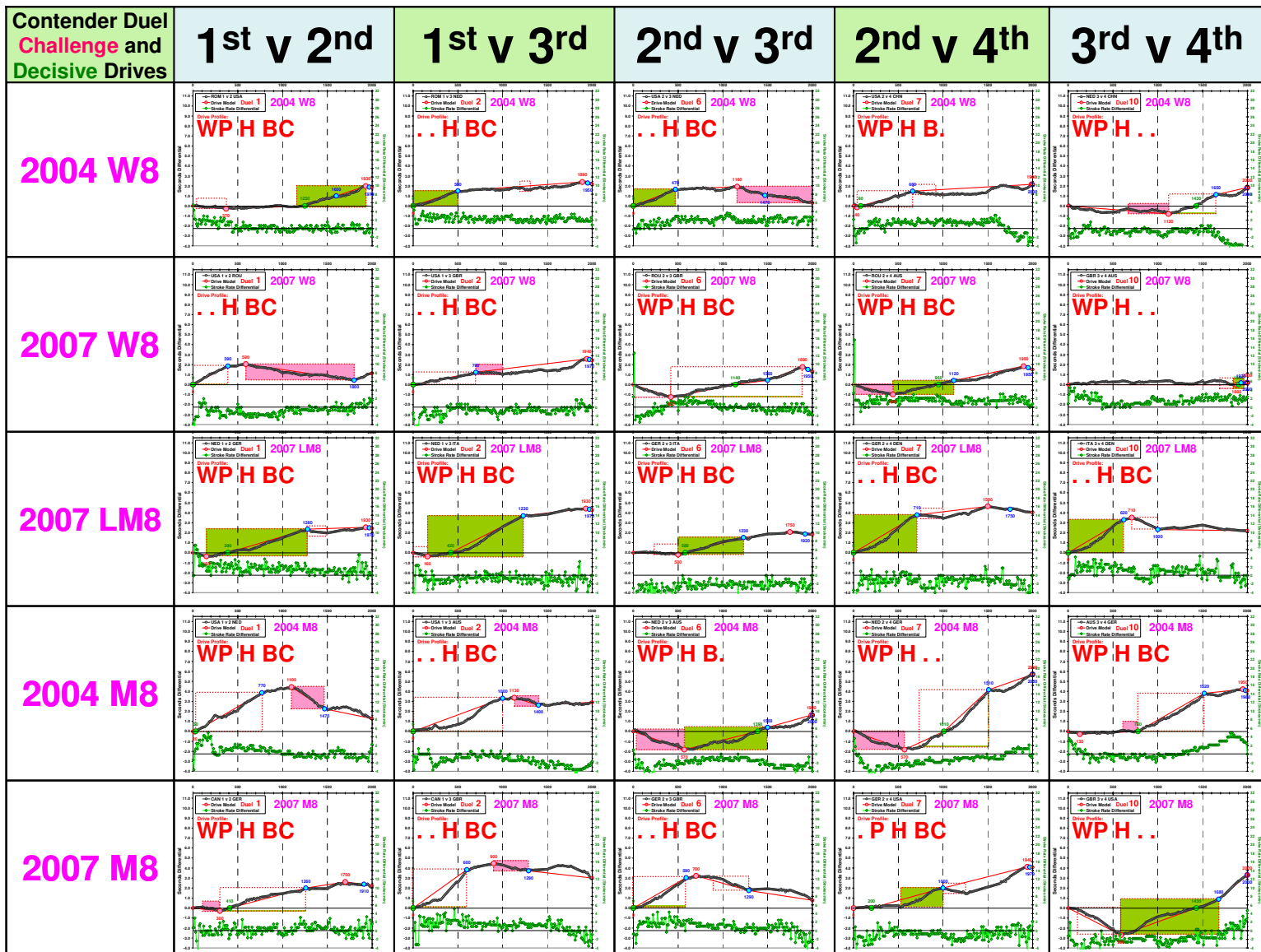
APPENDIX F: POSITION DUELS VS. MEDAL DUELS – DRIVE COMPARISONS

The decisive drives (in green) and the challenge drives (in pink) are highlighted in the following exhibits. The first exhibit is for the position duels, and the second exhibit is for the medals duels for each of the five races studied.

The race analyst uses subjective judgment in identifying these drives. Criteria considered includes where the slopes of the graphs appear to change (acceleration points). There is only one decisive drive in each duel – where the eventually winning crew takes the lead for good. However, there can be multiple challenge drives – before or after the decisive drive. Therefore, the race analyst must choose which drive appears to have posed the most critical challenge to the winning crew in the duel.

An alternative to studying the patterns of decisive and challenge “drives” is to study the decisive and challenge “totals.” This replaces subjectivity with identifying the maximum gains by the winning and losing crews. If you zoom in and study the following exhibits closely, it is clear that the identified drives understate the total range of distance closed by crews on each other. This also has the effect that the identified drives are steeper and shorter than totals, thus providing a better indicator of the closing rate at which crews are capable of moving on each other.



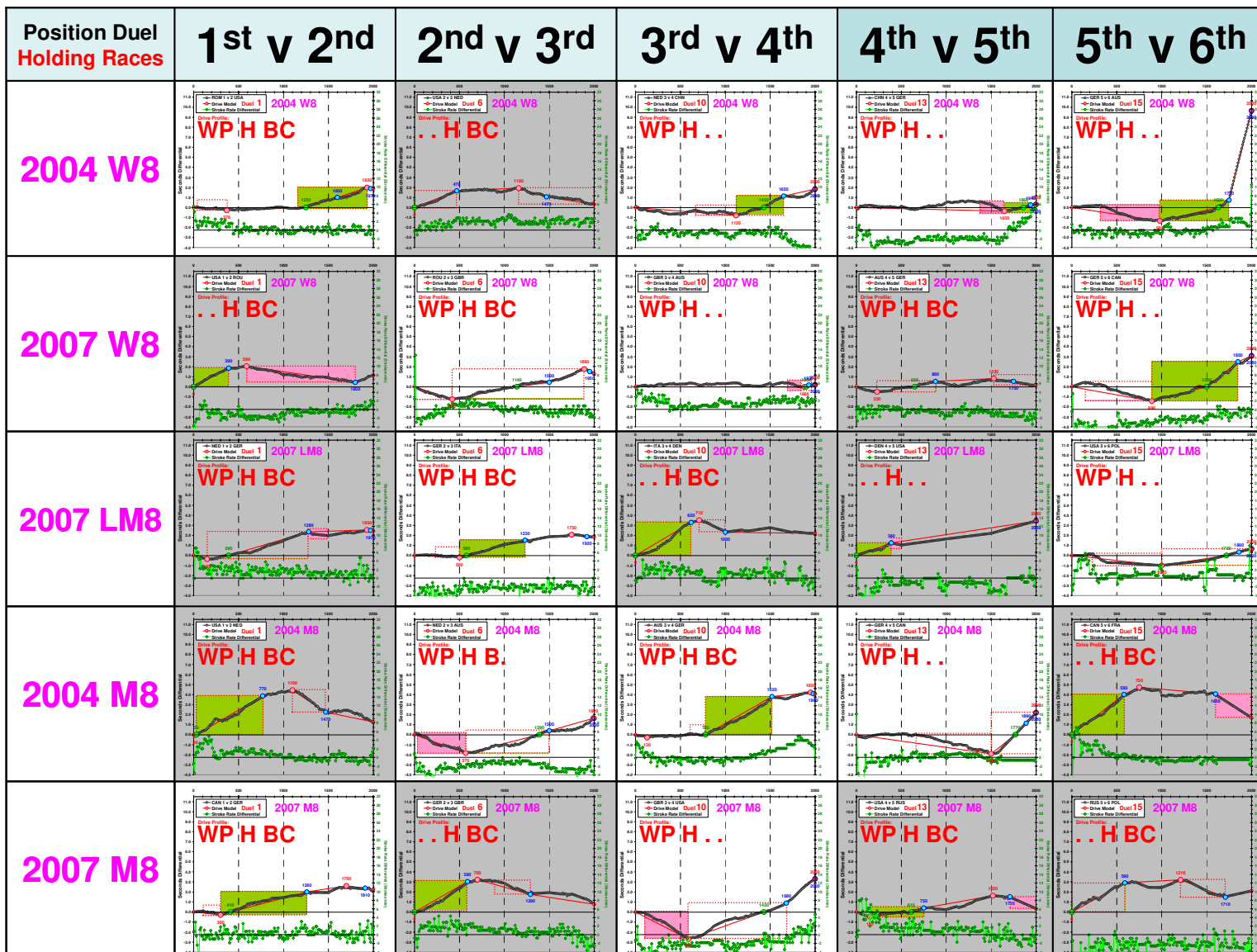


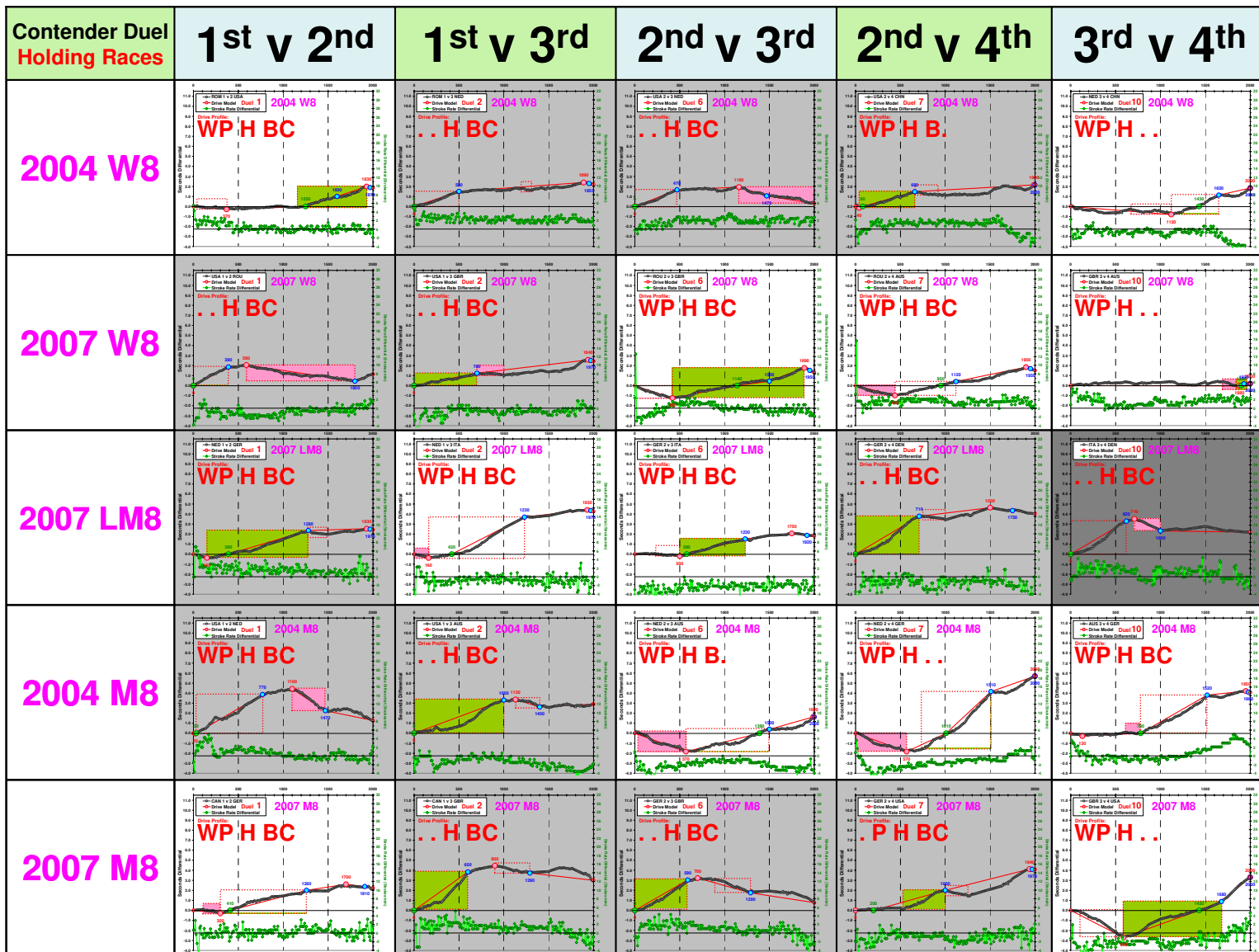
APPENDIX G: POSITION DUELS VS. MEDAL DUELS – HOLDING RACES

Position and medals duels can also be classified into those races that primarily follow the classic holding race pattern. Every come-from-behind race eventually turns into a holding race at some point, but not all holding races have a section of the race where the eventual winner needs to come from behind before taking the lead for good.

The races shaded in grey are identified to be primarily holding races. Note that the EEVA software will sometimes identify a short spotting segment as evidenced by the WP coding for the race profile. Technically, these are come-from-behind races, but these short leads are trivial and are subjectively excluded when identifying the holding races (shaded in grey).

For the five races studied, 11 of the 25 position duels are primarily holding races. 13 of the 25 medals duels are holding races. The inclusion of the green shaded medals races increased the frequency of holding races (7 of 10 duels). This would seem to be an expected result since duels between 1st and 3rd and duels between 2nd and 4th should tend to be more lopsided races than position duels. This pattern is one of the reasons why the decisive and closing drives analysis in this paper is limited to position duels, and not medals duels.





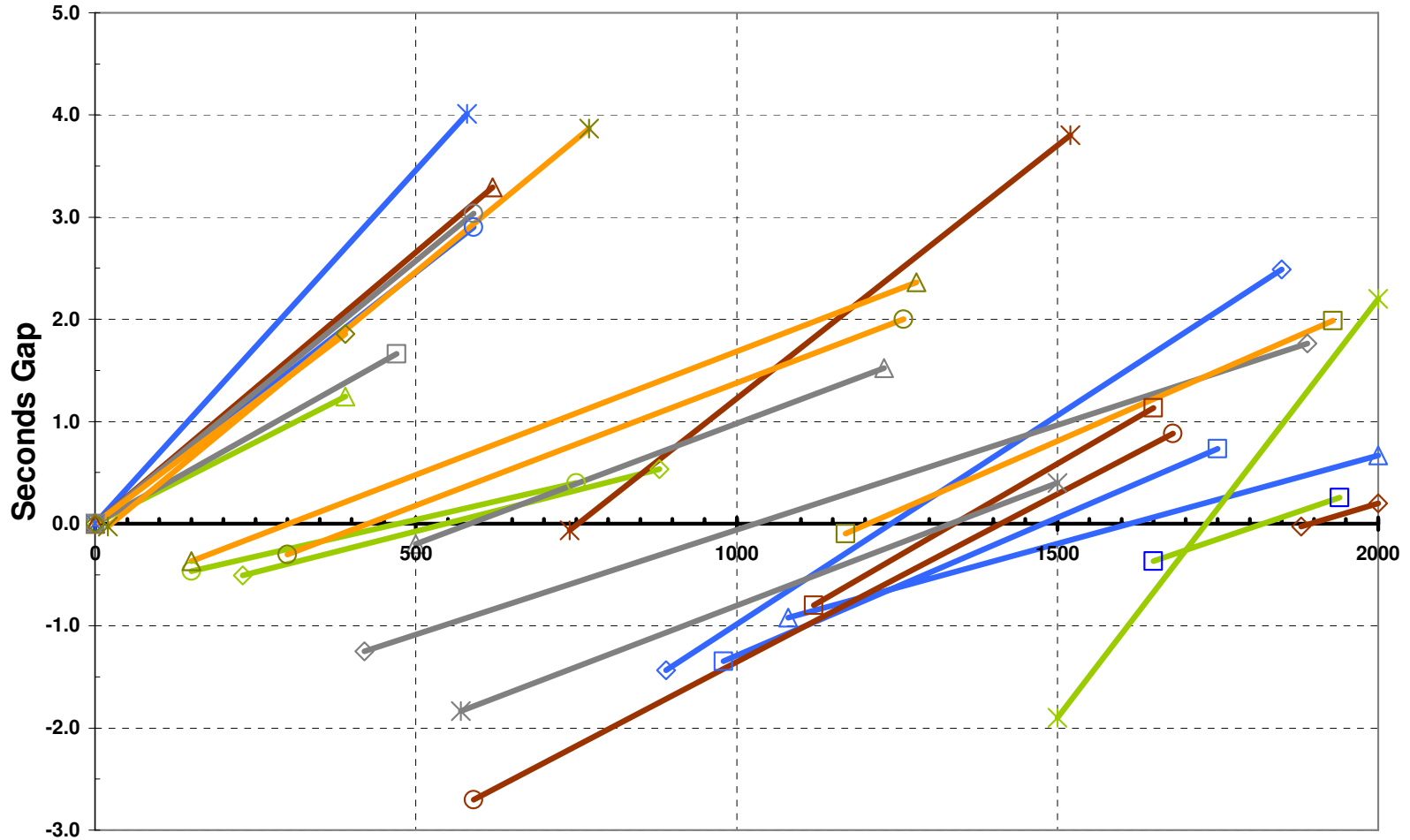
APPENDIX H: DECISIVE DRIVES COMPARED WITH DECISIVE TOTALS

The locations and slopes of decisive drives and decisive totals are illustrated in the following two “pickup sticks” graphs. The subjective manner in which decisive drives are selected will have the effect that decisive drives tend to have higher slopes and shorter durations than decisive totals. Visually comparing these two graphs against each other can illustrate this effect.

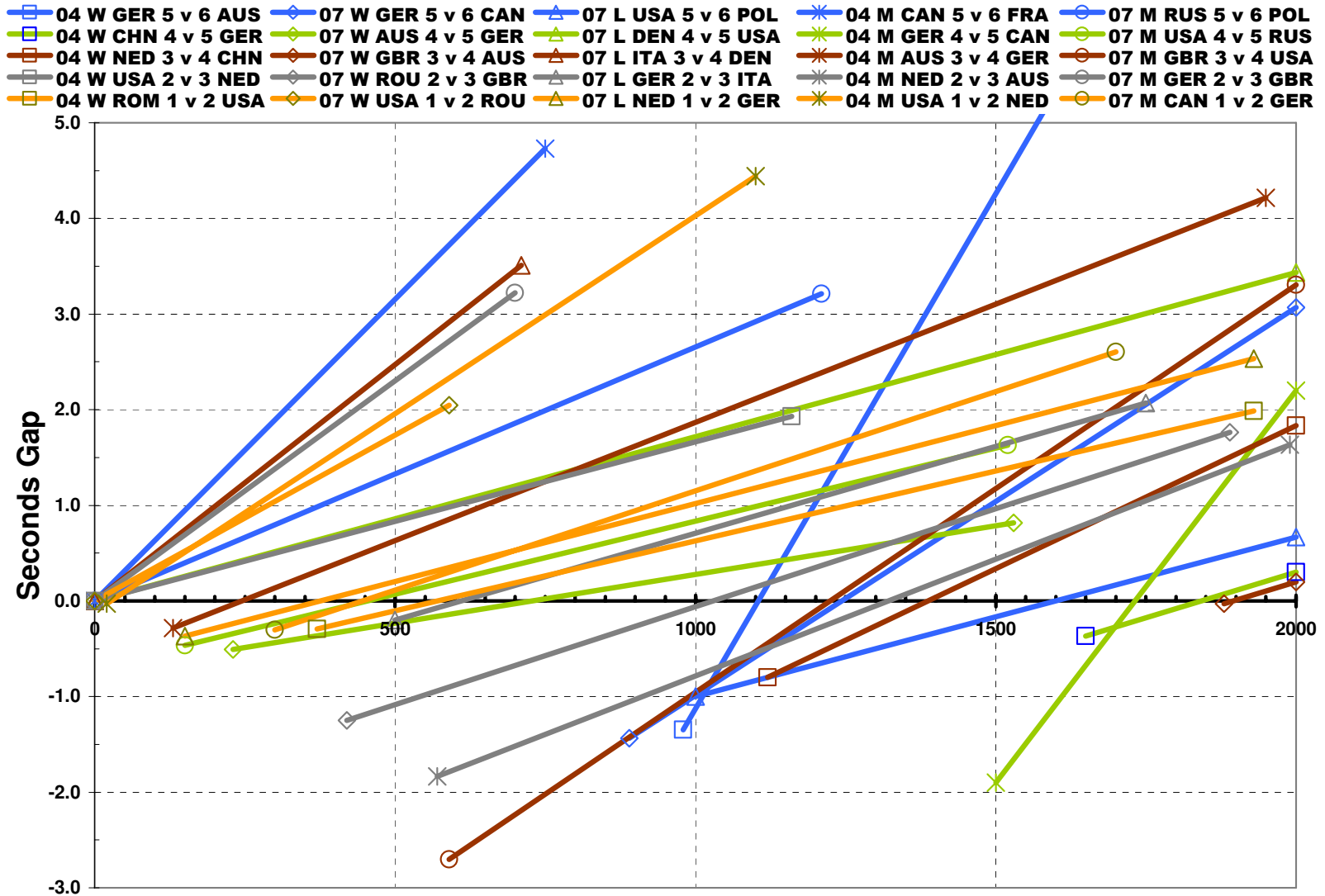
This effect can also be analyzed and quantified as illustrated on the next two point graphs with third order polynomial trend lines overlaid on the points. For the 25 position duels studied in this research, the average duration of drives is much different for decisive drives and decisive totals, while the average slopes are only slightly different.

Drive Patterns: Decisive Drives

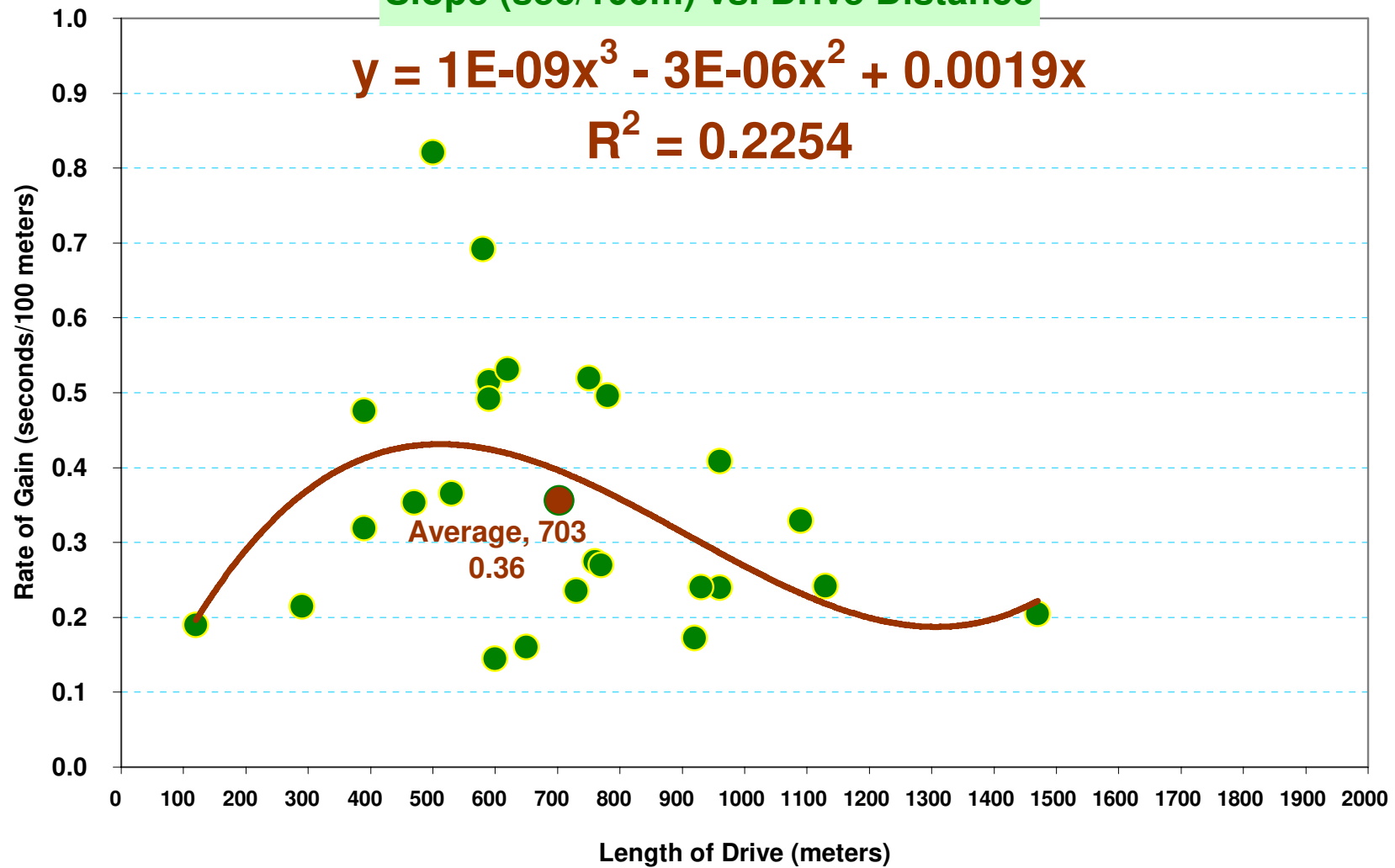
- 04 W GER 5 v 6 AUS 07 W GER 5 v 6 CAN 07 L USA 5 v 6 POL 04 M CAN 5 v 6 FRA 07 M RUS 5 v 6 POL
- 04 W CHN 4 v 5 GER 07 W AUS 4 v 5 GER 07 L DEN 4 v 5 USA 04 M GER 4 v 5 CAN 07 M USA 4 v 5 RUS
- 04 W NED 3 v 4 CHN 07 W GBR 3 v 4 AUS 07 L ITA 3 v 4 DEN 04 M AUS 3 v 4 GER 07 M GBR 3 v 4 USA
- 04 W USA 2 v 3 NED 07 W ROU 2 v 3 GBR 07 L GER 2 v 3 ITA 04 M NED 2 v 3 AUS 07 M GER 2 v 3 GBR
- 04 W ROM 1 v 2 USA 07 W USA 1 v 2 ROU 07 L NED 1 v 2 GER 04 M USA 1 v 2 NED 07 M CAN 1 v 2 GER



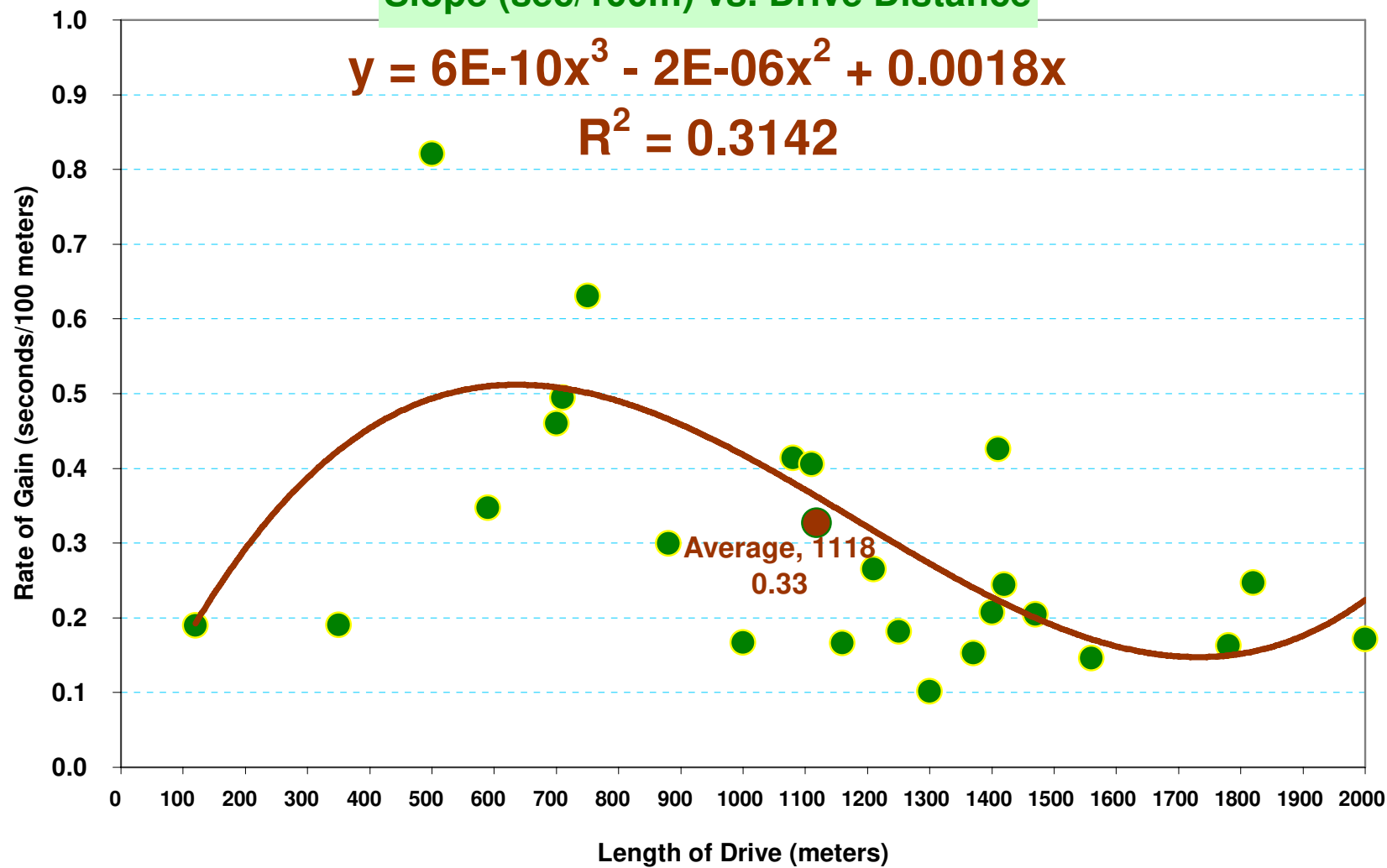
Drive Patterns: Decisive Totals



Decisive Drive Analysis
Slope (sec/100m) vs. Drive Distance



Decisive Totals Analysis
Slope (sec/100m) vs. Drive Distance



APPENDIX I: CHALLENGE DRIVES COMPARED WITH CHALLENGE TOTALS

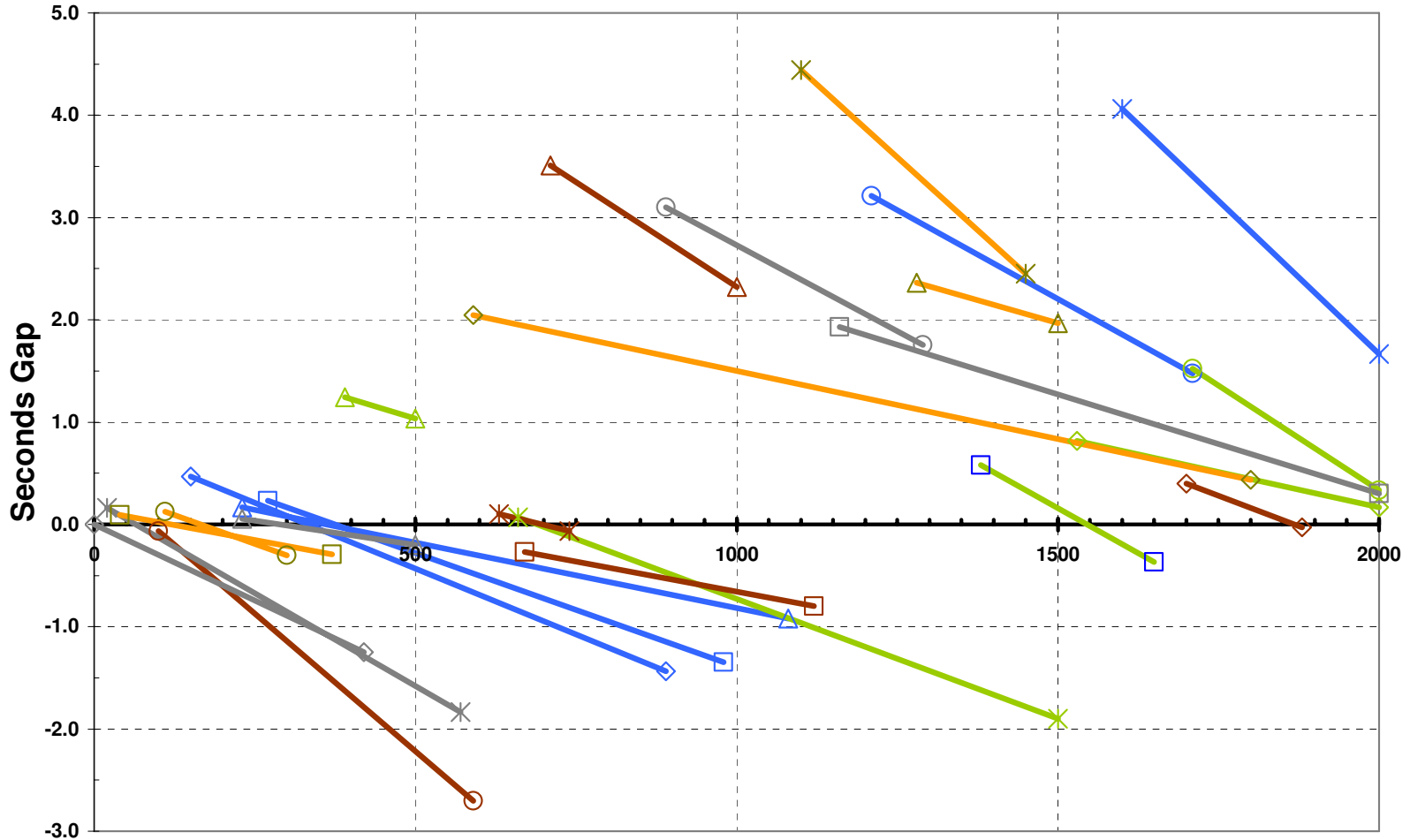
The locations and slopes of challenge drives and challenge totals are illustrated in the following two “pickup sticks” graphs. The subjective manner in which challenge drives are selected has the effect that challenge drives tend to have higher slopes and shorter durations than challenge totals. Visually comparing these two graphs against each other illustrates this effect.

This effect can also be analyzed and quantified as illustrated on the next two point graphs with third order polynomial trend lines overlaid on the points. For the 25 position duels studied in this research, the trend equations for challenge drives and challenge totals are much different in all of their parameters.

The effect of limiting analysis to “drives” rather than “totals” seems more critical to analyzing challenge drives than decisive drives. All four of these decisive/challenge and drives/totals combinations are illustrated on a single page to make these comparisons easier to compare.

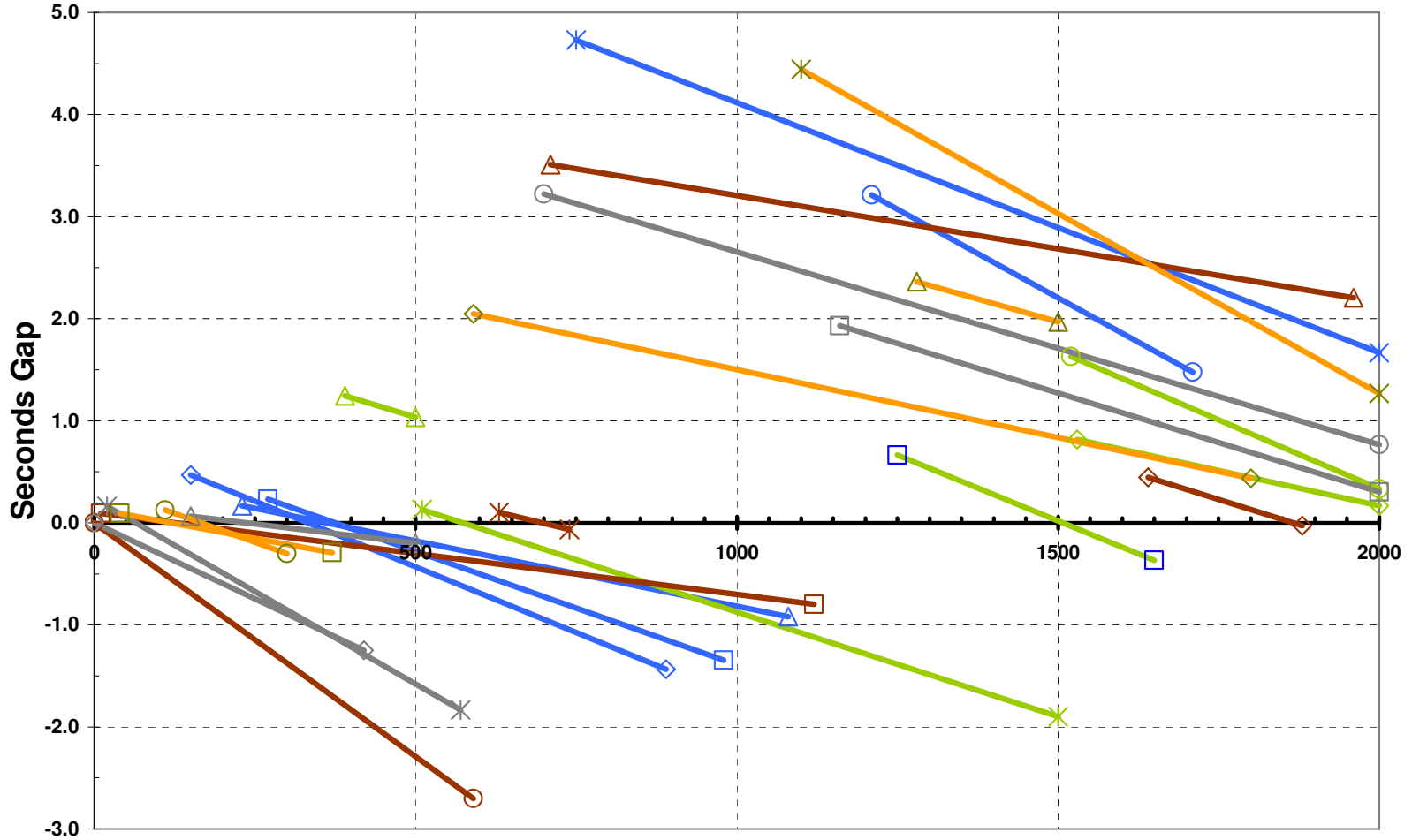
Drive Patterns: Challenge Drives

- 04 W GER 5 v 6 AUS 07 W GER 5 v 6 CAN 07 L USA 5 v 6 POL 04 M CAN 5 v 6 FRA 07 M RUS 5 v 6 POL
- 04 W CHN 4 v 5 GER 07 W AUS 4 v 5 GER 07 L DEN 4 v 5 USA 04 M GER 4 v 5 CAN 07 M USA 4 v 5 RUS
- 04 W NED 3 v 4 CHN 07 W GBR 3 v 4 AUS 07 L ITA 3 v 4 DEN 04 M AUS 3 v 4 GER 07 M GBR 3 v 4 USA
- 04 W USA 2 v 3 NED 07 W ROU 2 v 3 GBR 07 L GER 2 v 3 ITA 04 M NED 2 v 3 AUS 07 M GER 2 v 3 GBR
- 04 W ROM 1 v 2 USA 07 W USA 1 v 2 ROU 07 L NED 1 v 2 GER 04 M USA 1 v 2 NED 07 M CAN 1 v 2 GER

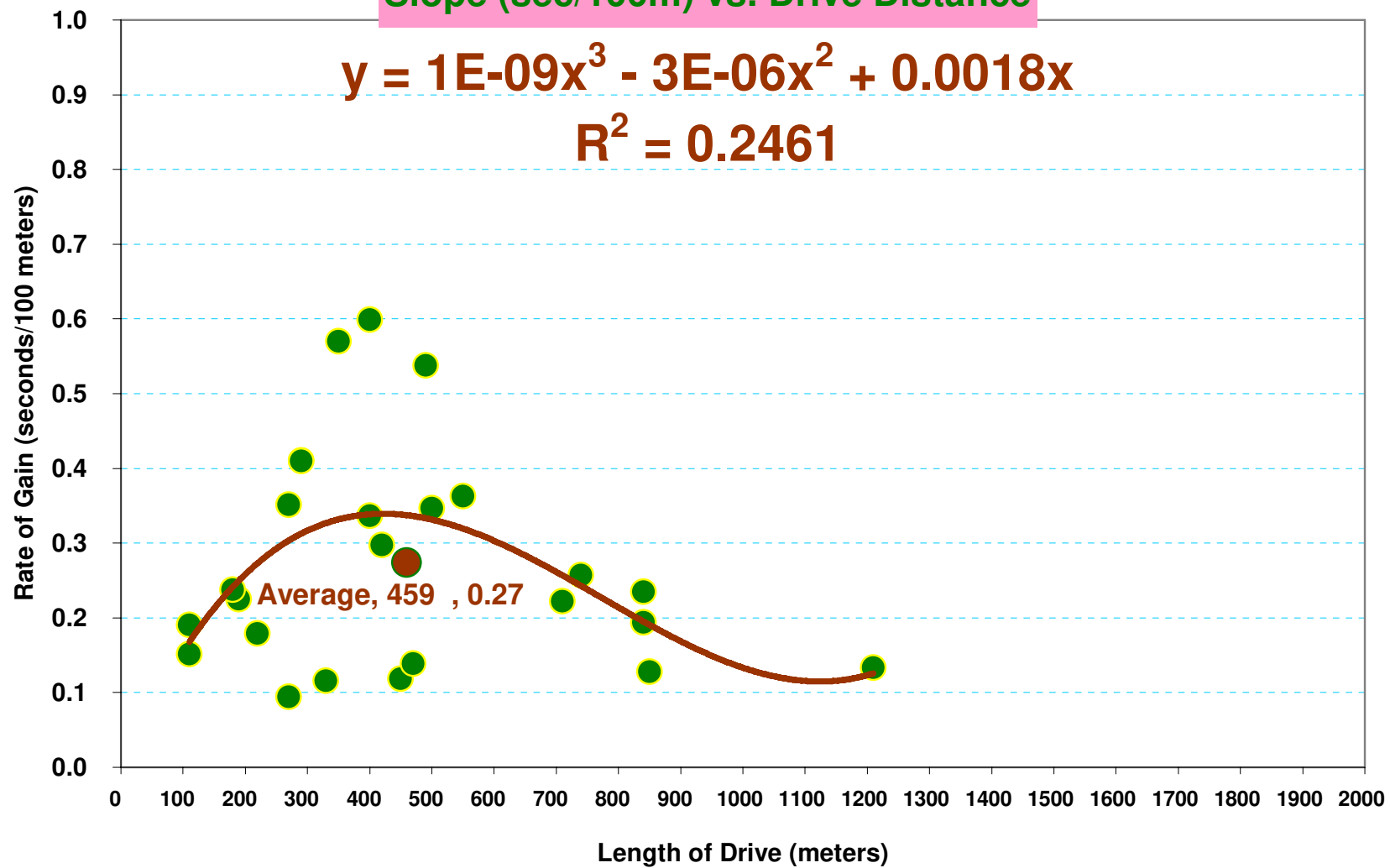


Drive Patterns: Challenge Totals

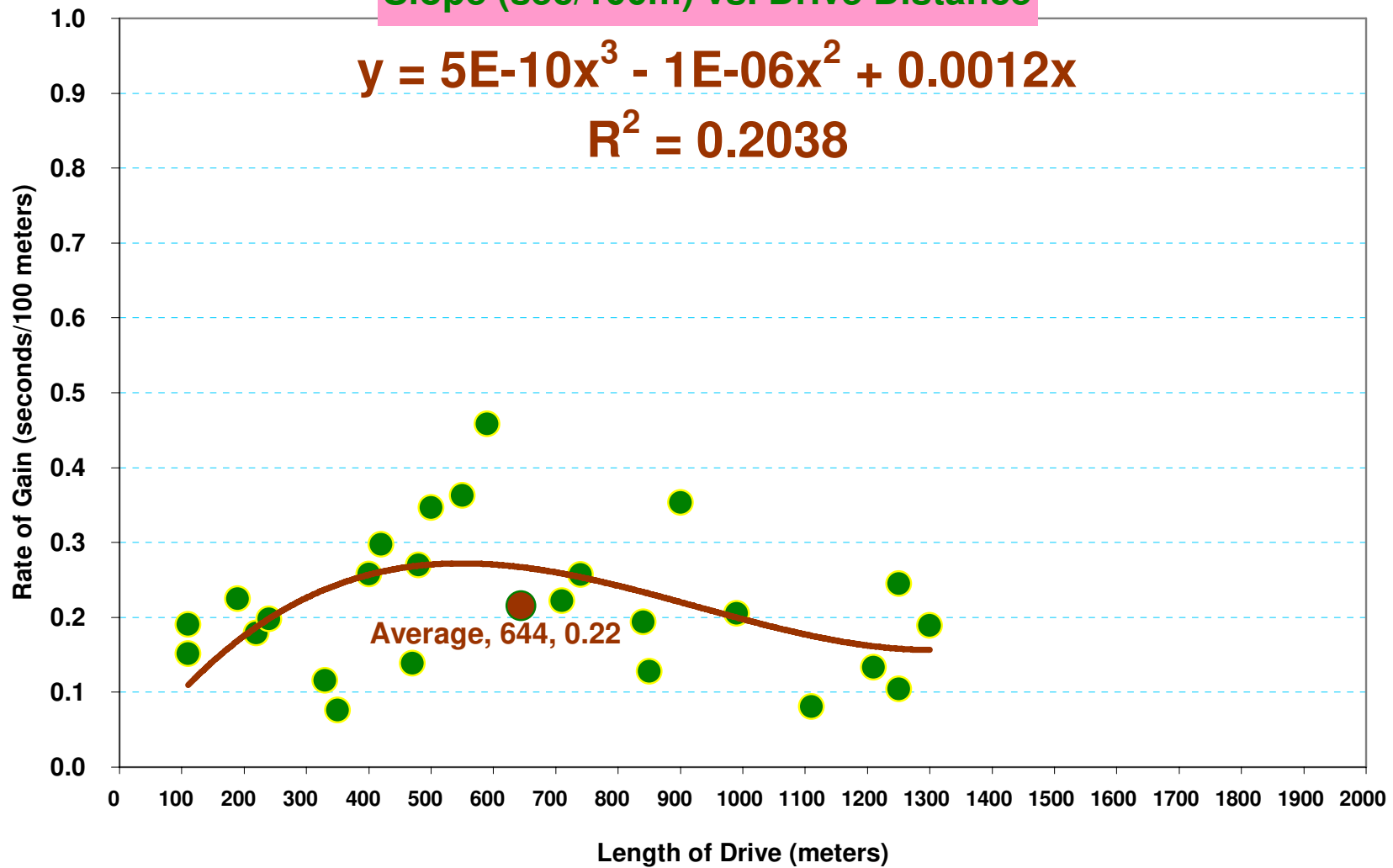
- 04 W GER 5 v 6 AUS 07 W GER 5 v 6 CAN 07 L USA 5 v 6 POL 04 M CAN 5 v 6 FRA 07 M RUS 5 v 6 POL
- 04 W CHN 4 v 5 GER 07 W AUS 4 v 5 GER 07 L DEN 4 v 5 USA 04 M GER 4 v 5 CAN 07 M USA 4 v 5 RUS
- 04 W NED 3 v 4 CHN 07 W GBR 3 v 4 AUS 07 L ITA 3 v 4 DEN 04 M AUS 3 v 4 GER 07 M GBR 3 v 4 USA
- 04 W USA 2 v 3 NED 07 W ROU 2 v 3 GBR 07 L GER 2 v 3 ITA 04 M NED 2 v 3 AUS 07 M GER 2 v 3 GBR
- 04 W ROM 1 v 2 USA 07 W USA 1 v 2 ROU 07 L NED 1 v 2 GER 04 M USA 1 v 2 NED 07 M CAN 1 v 2 GER

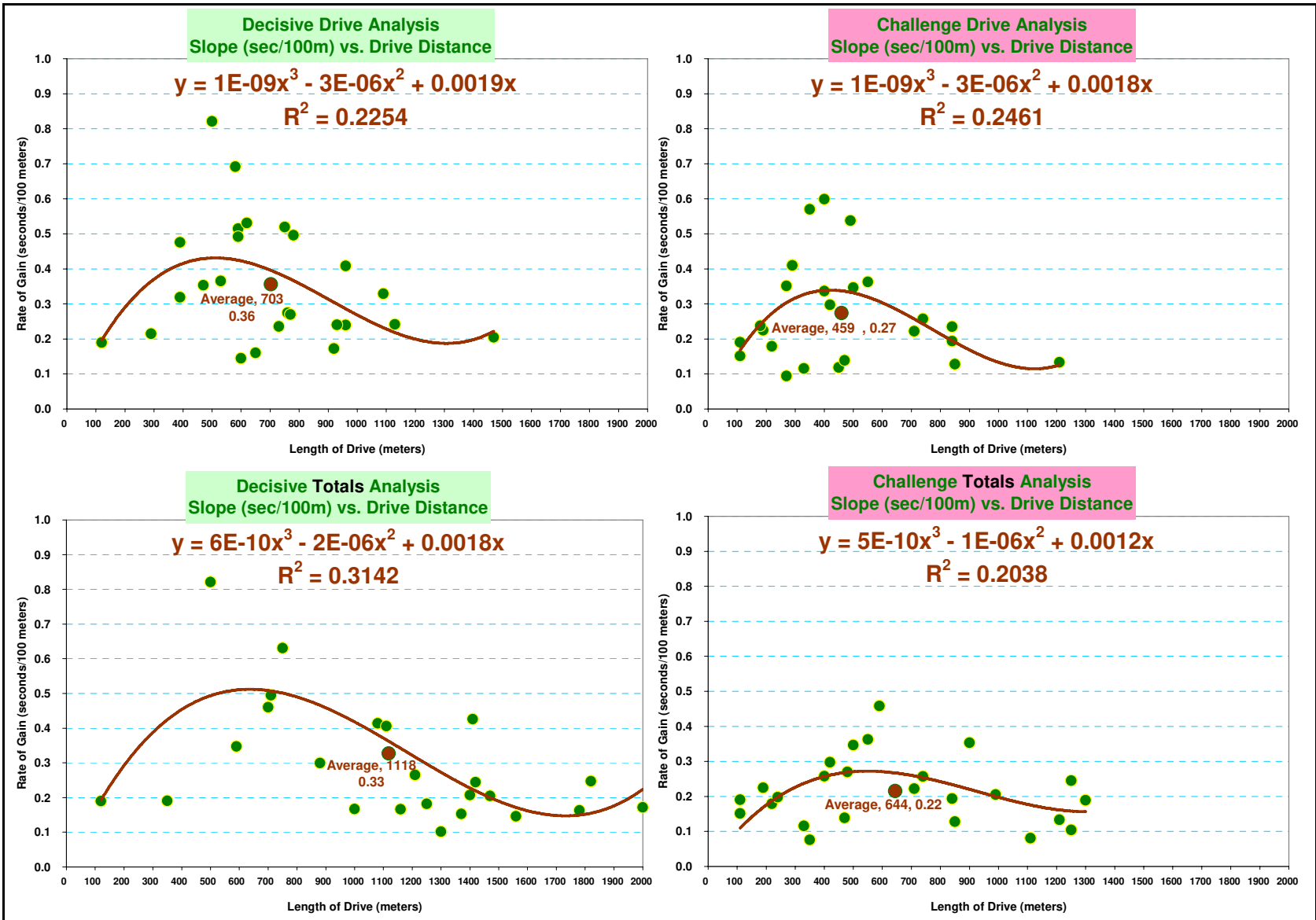


Challenge Drive Analysis
Slope (sec/100m) vs. Drive Distance



Challenge Totals Analysis
Slope (sec/100m) vs. Drive Distance





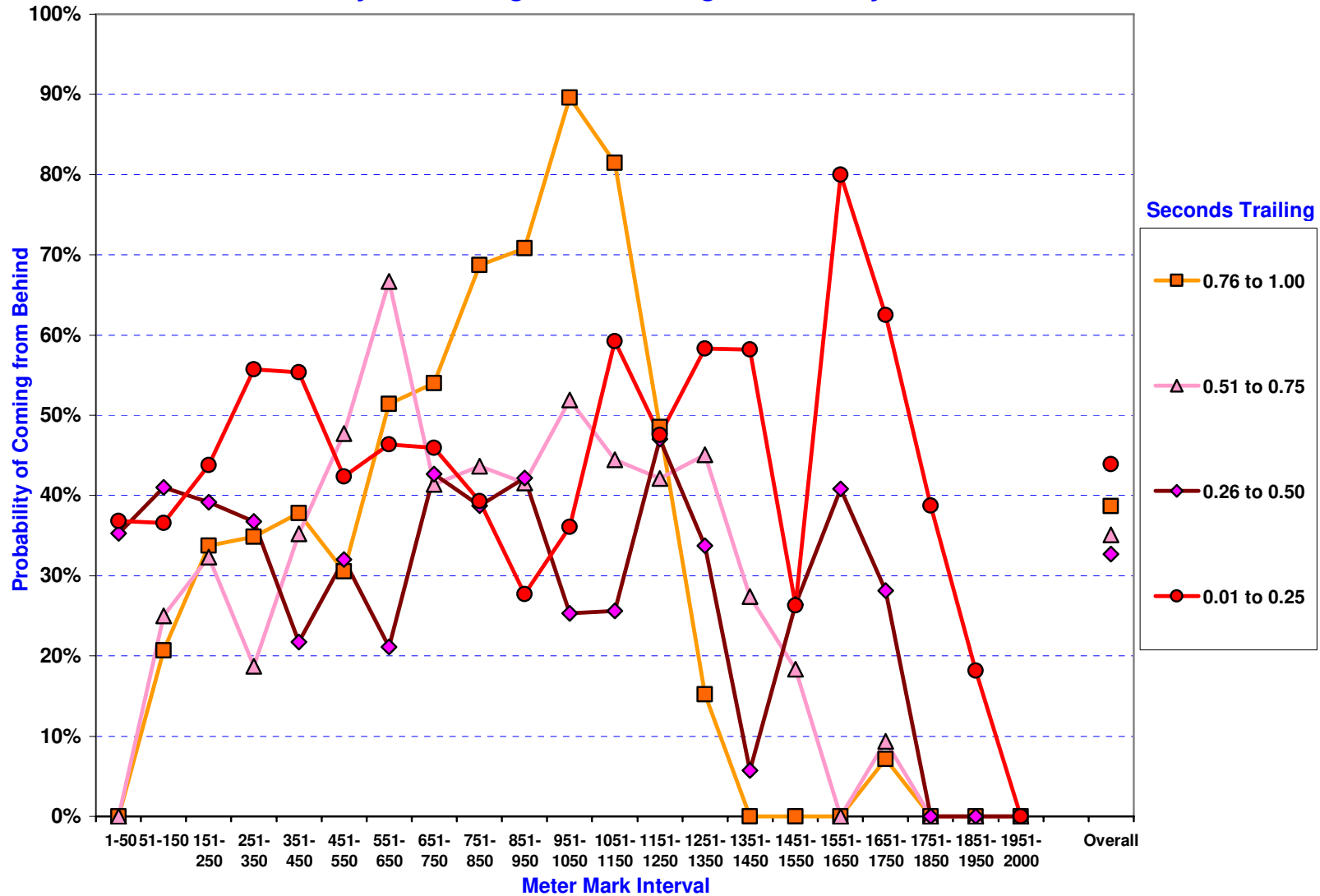
APPENDIX J: PROBABILITY OF WINNING WHEN TRAILING IN A DUEL

Video analysis of five races yields a database of 75 duels observations at each of 200 points along the 2000-meter race course. Observations of relative position in these duels can be classified according to whether or not the eventual winning crew is currently in the lead at each point along the course. Thus, it is possible to calculate the percentage of leads that are eventually lost at the end of the race. This also means the percentage of times that a lead is eventually overcome in come-from-behind manner.

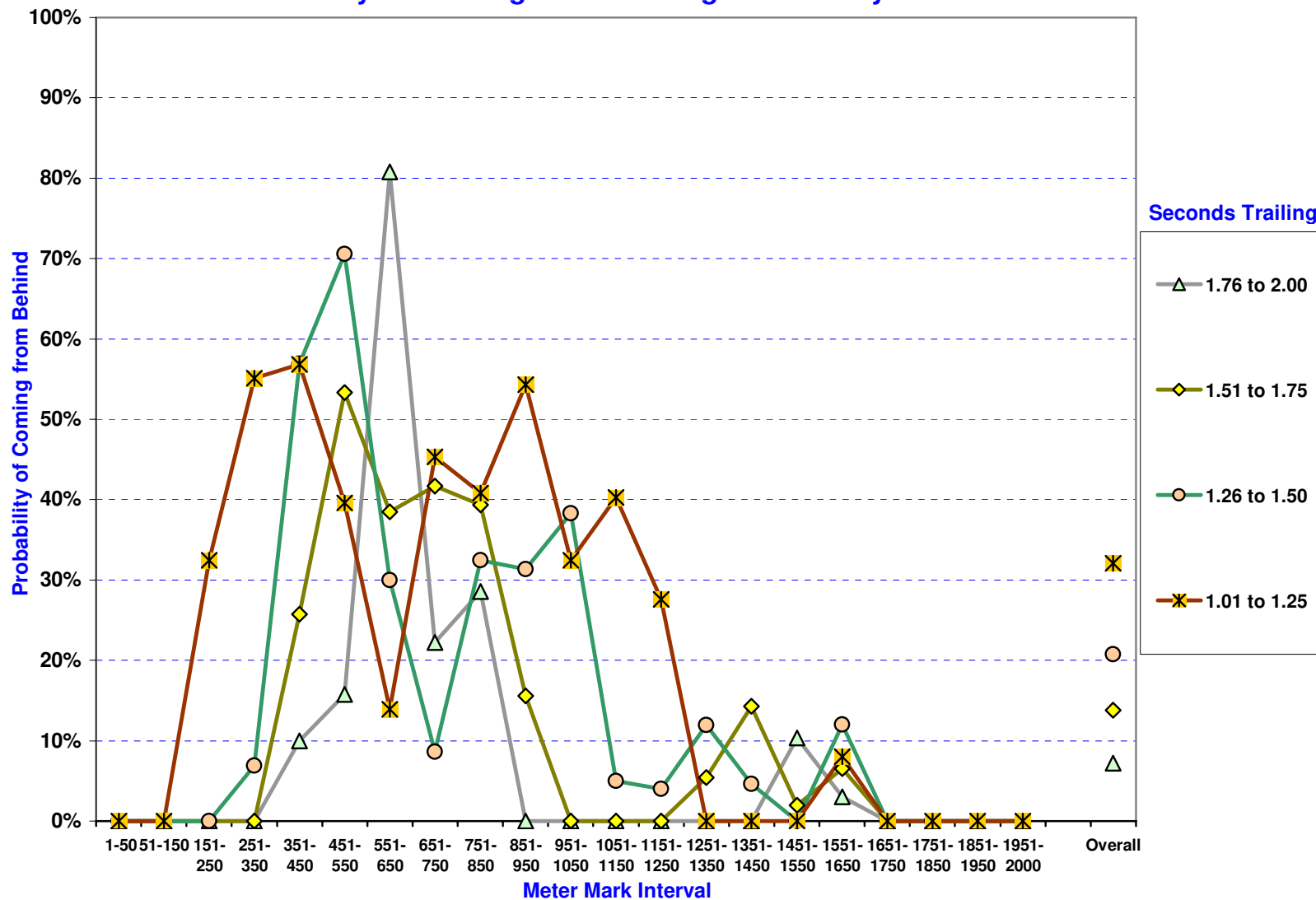
Leads can be categorized into various intervals including quarter second margins and full second margins as shown on the following graphs. Statistics are aggregated into 100-meter intervals along the race course (except for the first and last 50-meter intervals on the course).

The general pattern is intuitive in that shorter leads are less decisive and more likely to be overcome by the end of the race. Probabilities vary by position along the course. The overall probabilities of coming from behind to win when trailing in a duel are 38%, 20% and 4% for leads of 0-1 second, 1-2 seconds, and 2-3 seconds respectively.

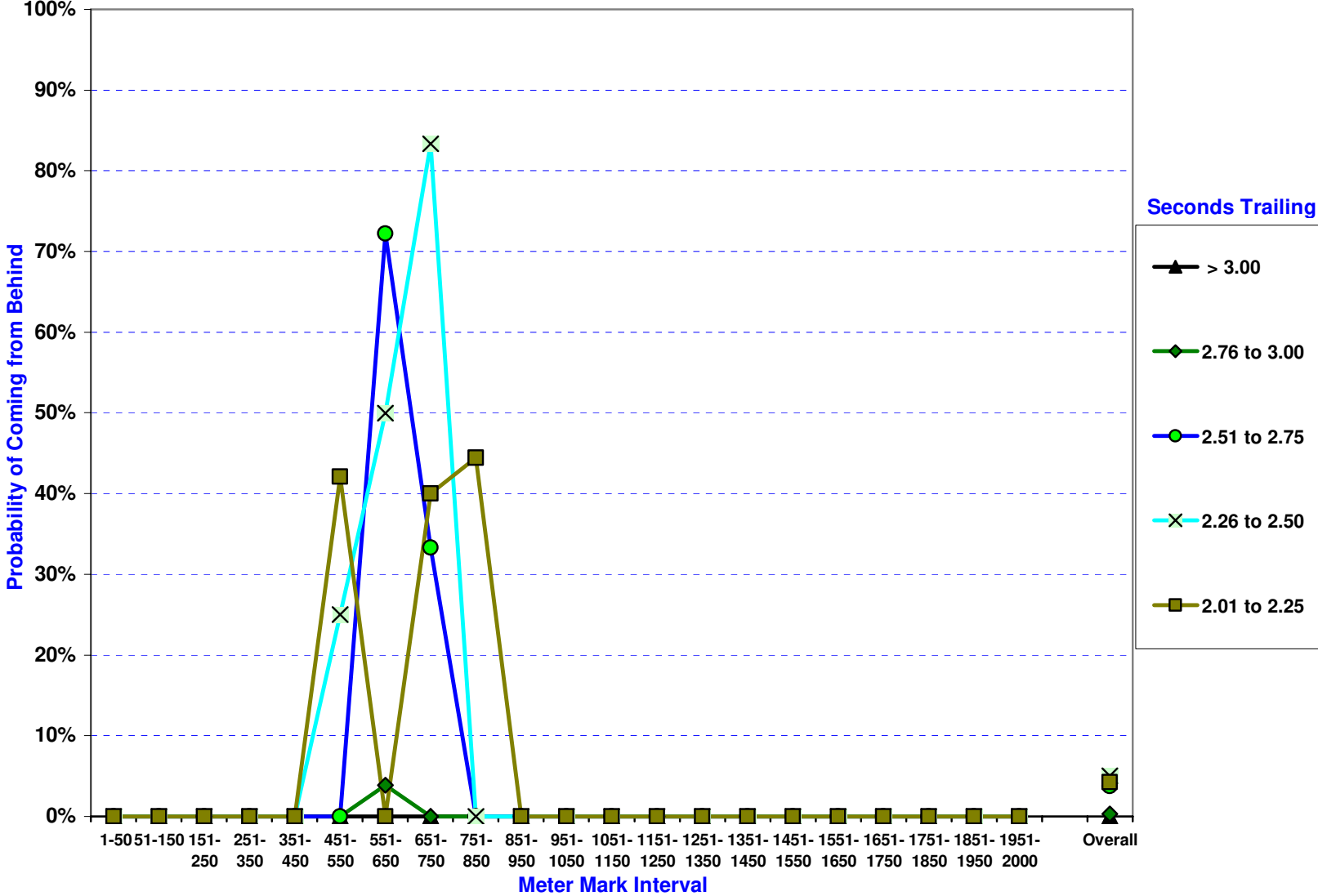
Probability of Winning when Trailing in a Duel by 0-1.00 Seconds



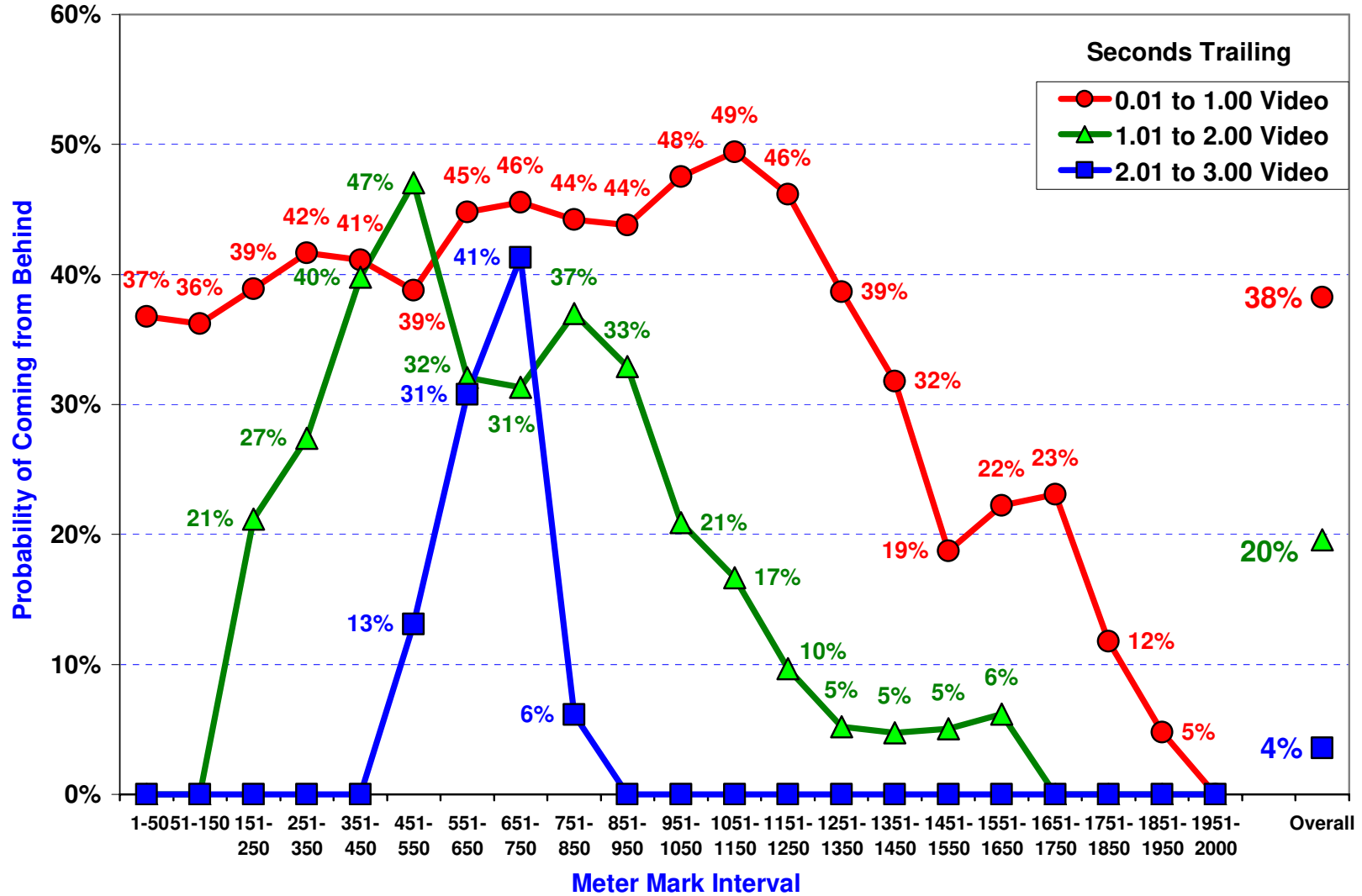
Probability of Winning when Trailing in a Duel by 1-2.00 Seconds



Probability of Winning when Trailing in a Duel by 2-3.00 Seconds



Probability of Winning when Trailing in a Duel



APPENDIX K: PROBABILITY OF WINNING – VIDEO VS. SPLITS ANALYSES

Video analysis is very time consuming, so only 5 races were studied in this research. As a validation of this research, probabilities based on video analysis were compared against probabilities from published splits of all world and Olympic championship finals in eights competition from 2001-2008. Analyzing published splits allow 315 duels to be analyzed and compared against the results from video analysis of 75 duels. The probability analysis is identical, but the video analysis allows probabilities to be computed all along the course. Splits-based analysis allows probabilities to be computed at only the 500-meter points.

The following tables summarize the counts and probabilities from each of these two data sources. Results are graphically compared, and second order trend lines applied to illustrate the general patterns observed.

Frequency Counts for Video-Based Probabilities

Data is aggregated into larger race intervals from observations recorded at 10-meter intervals

Race Interval	-2.01 to -3.00	-1.01 to 2.00	-0.01 to -1.00	0.01 to 1.00	1.01 to 2.00	2.01 to 3.00
1-50	0	0	129	222	0	0
51-150	0	0	261	460	3	0
151-250	0	25	242	380	93	2
251-350	0	63	205	287	167	25
351-450	0	80	169	242	121	109
451-550	17	64	154	243	72	113
551-650	20	59	147	181	125	45
651-750	19	72	128	153	158	27
751-850	4	94	103	130	160	61
851-950	0	77	106	136	157	53
951-1050	0	42	125	138	159	66
1051-1150	0	32	132	135	160	60
1151-1250	0	17	126	147	159	52
1251-1350	0	10	94	149	182	72
1351-1450	0	10	61	131	201	108
1451-1550	0	10	33	143	188	123
1551-1650	0	10	36	126	152	171
1651-1750	0	0	30	100	155	168
1751-1850	0	0	12	90	130	157
1851-1950	0	0	4	80	129	145
1951-2000	0	0	0	39	59	68
Overall	60	665	2297	3712	2730	1625

Frequency Counts for Splits-Based Probabilities

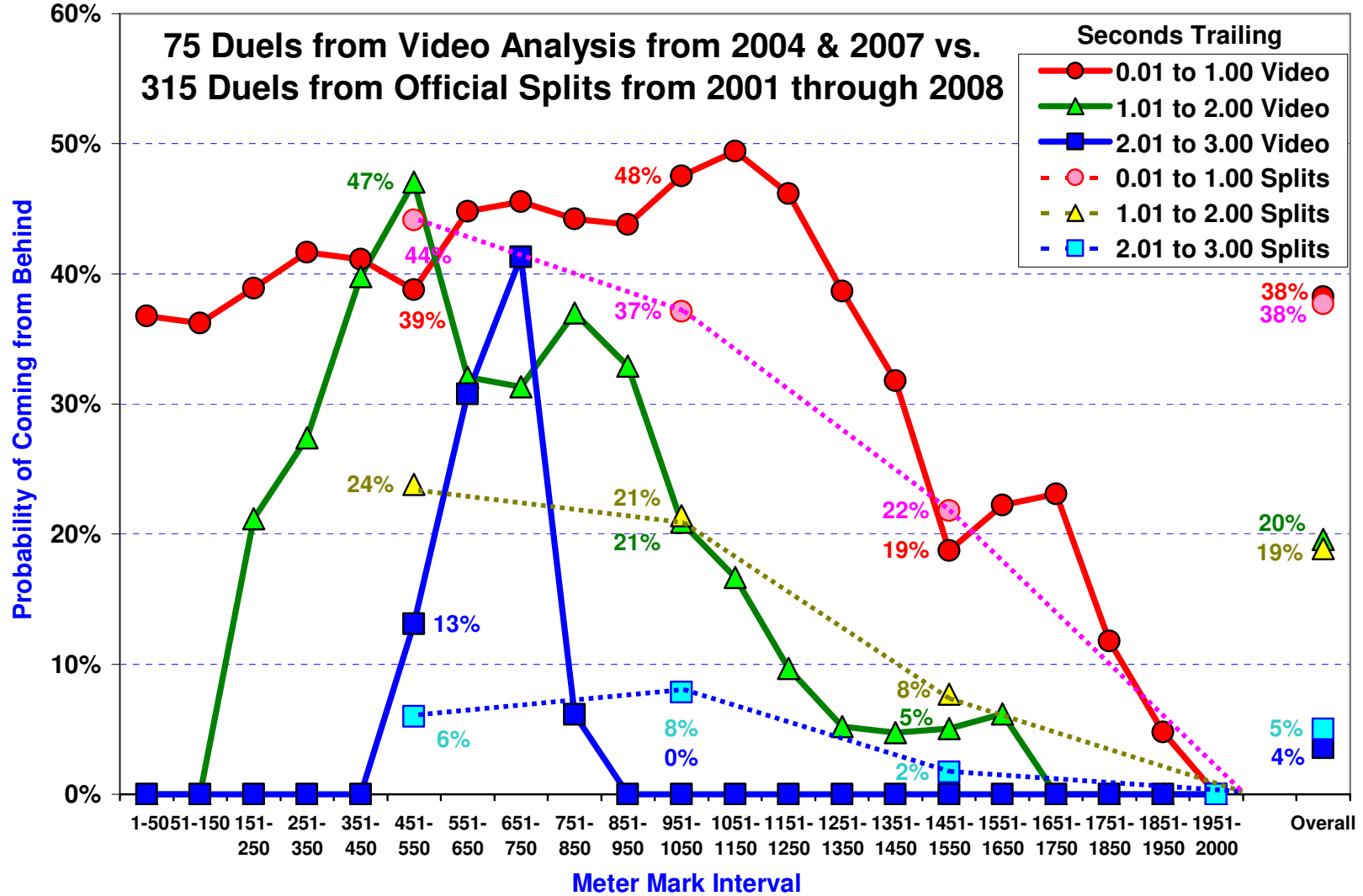
Data is measured only at the quarterly 500-meter markers

Race Interval	<-3.00	-2.01 to -3.00	-1.01 to 2.00	-0.01 to -1.00	0.01 to 1.00	1.01 to 2.00	2.01 to 3.00	>3.00	Duels
0									
500	1	3	25	64	81	80	47	14	315
1000	0	4	18	36	61	66	47	83	315
1500	0	1	5	12	43	60	58	136	315
2000	0	0	0	0	0	0	0	0	
Overall	1	8	48	112	185	206	152	233	945

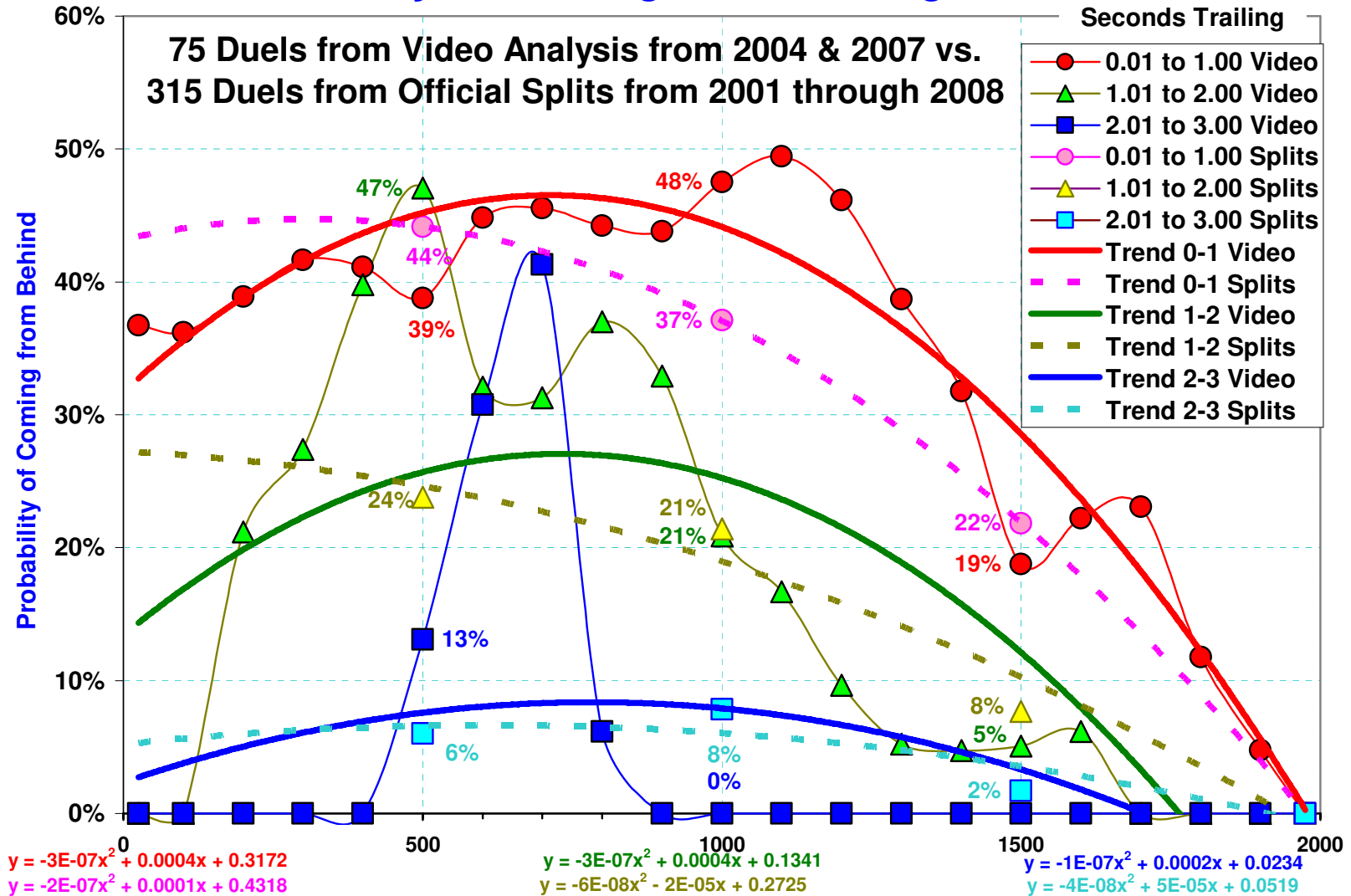
Probability of Coming from Behind in a Duel

Video Analysis				Splits Analysis				
Race Interval	0.01 to 1.00	1.01 to 2.00	2.01 to 3.00	Meter Mark	0.01 to 1.00	1.01 to 2.00	2.01 to 3.00	>3.00 Splits
1-50	36.8%			0				
51-150	36.2%	0.0%						
151-250	38.9%	21.2%	0.0%					
251-350	41.7%	27.4%	0.0%					
351-450	41.1%	39.8%	0.0%					
451-550	38.8%	47.1%	13.1%	500	44.1%	23.8%	6.0%	6.7%
551-650	44.8%	32.1%	30.8%					
651-750	45.6%	31.3%	41.3%					
751-850	44.2%	37.0%	6.2%					
851-950	43.8%	32.9%	0.0%					
951-1050	47.5%	20.9%	0.0%	1000	37.1%	21.4%	7.8%	0.0%
1051-1150	49.4%	16.7%	0.0%					
1151-1250	46.2%	9.7%	0.0%					
1251-1350	38.7%	5.2%	0.0%					
1351-1450	31.8%	4.7%	0.0%					
1451-1550	18.8%	5.1%	0.0%	1500	21.8%	7.7%	1.7%	0.0%
1551-1650	22.2%	6.2%	0.0%					
1651-1750	23.1%	0.0%	0.0%					
1751-1850	11.8%	0.0%	0.0%					
1851-1950	4.8%	0.0%	0.0%					
1951-2000	0.0%	0.0%	0.0%	2000	0.0%	0.0%	0.0%	0.0%
Overall	38.2%	19.6%	3.6%	Combined	37.7%	18.9%	5.0%	0.4%

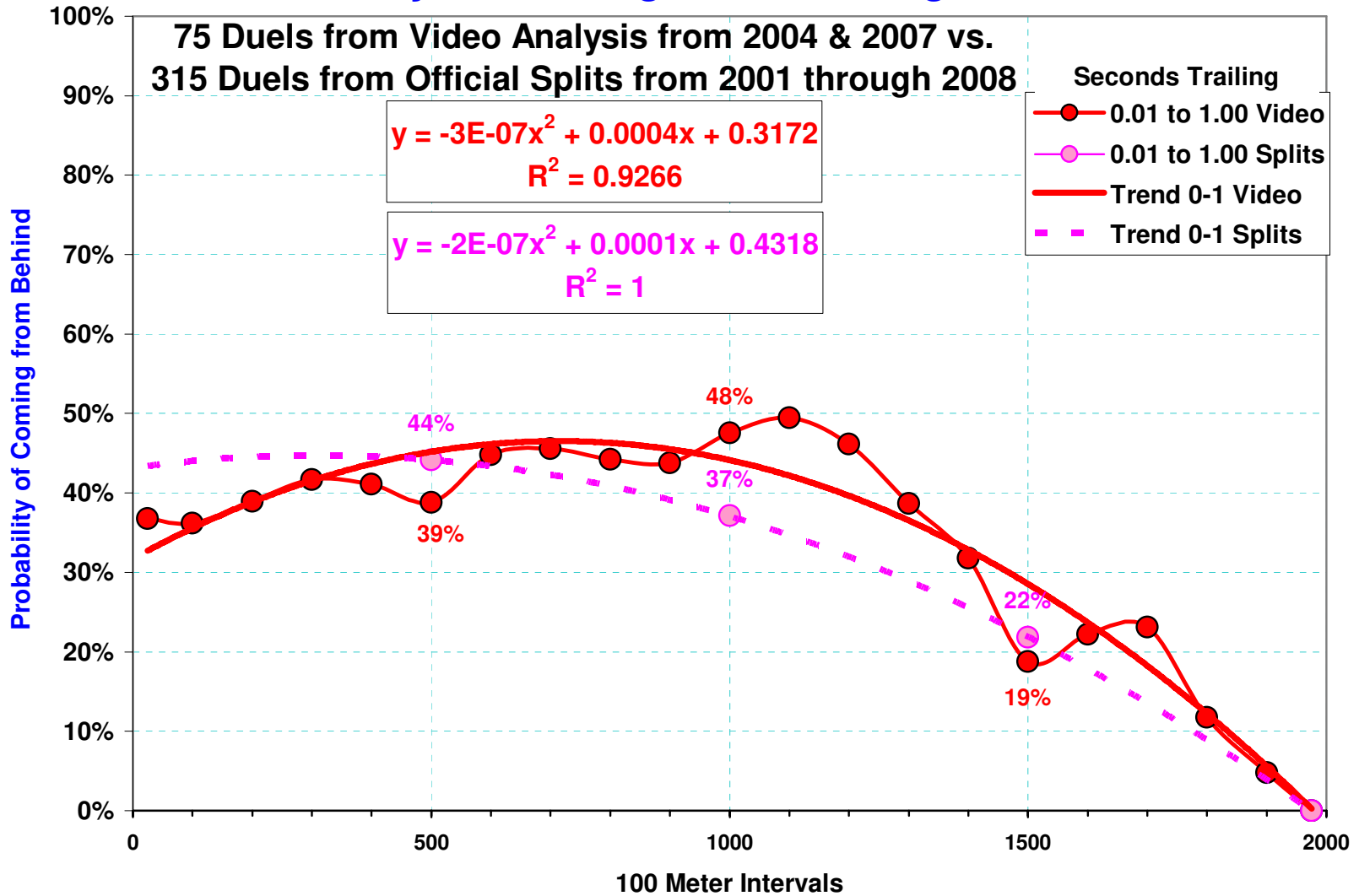
Probability of Winning when Trailing in a Duel



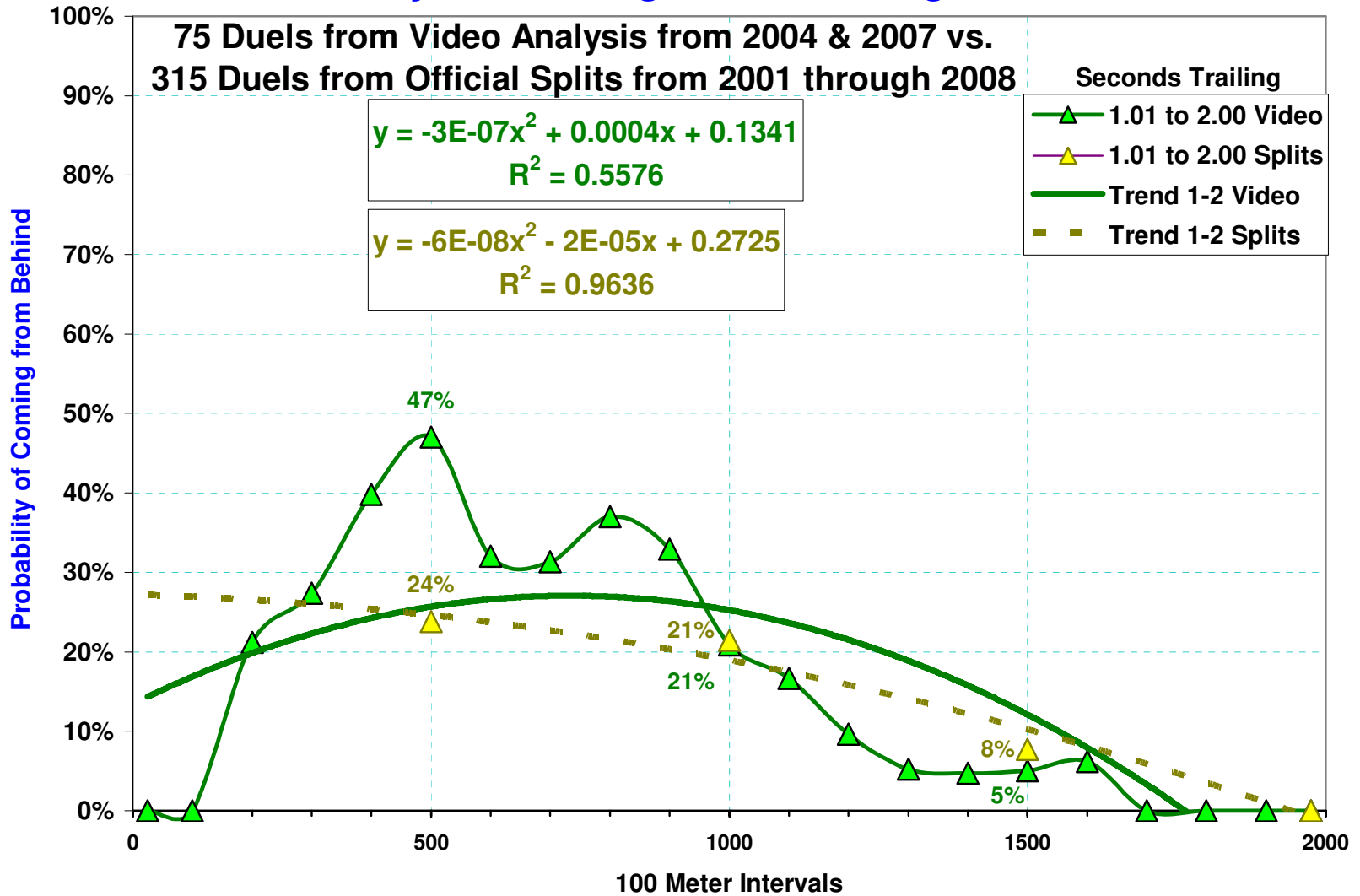
Probability of Winning when Trailing in a Duel



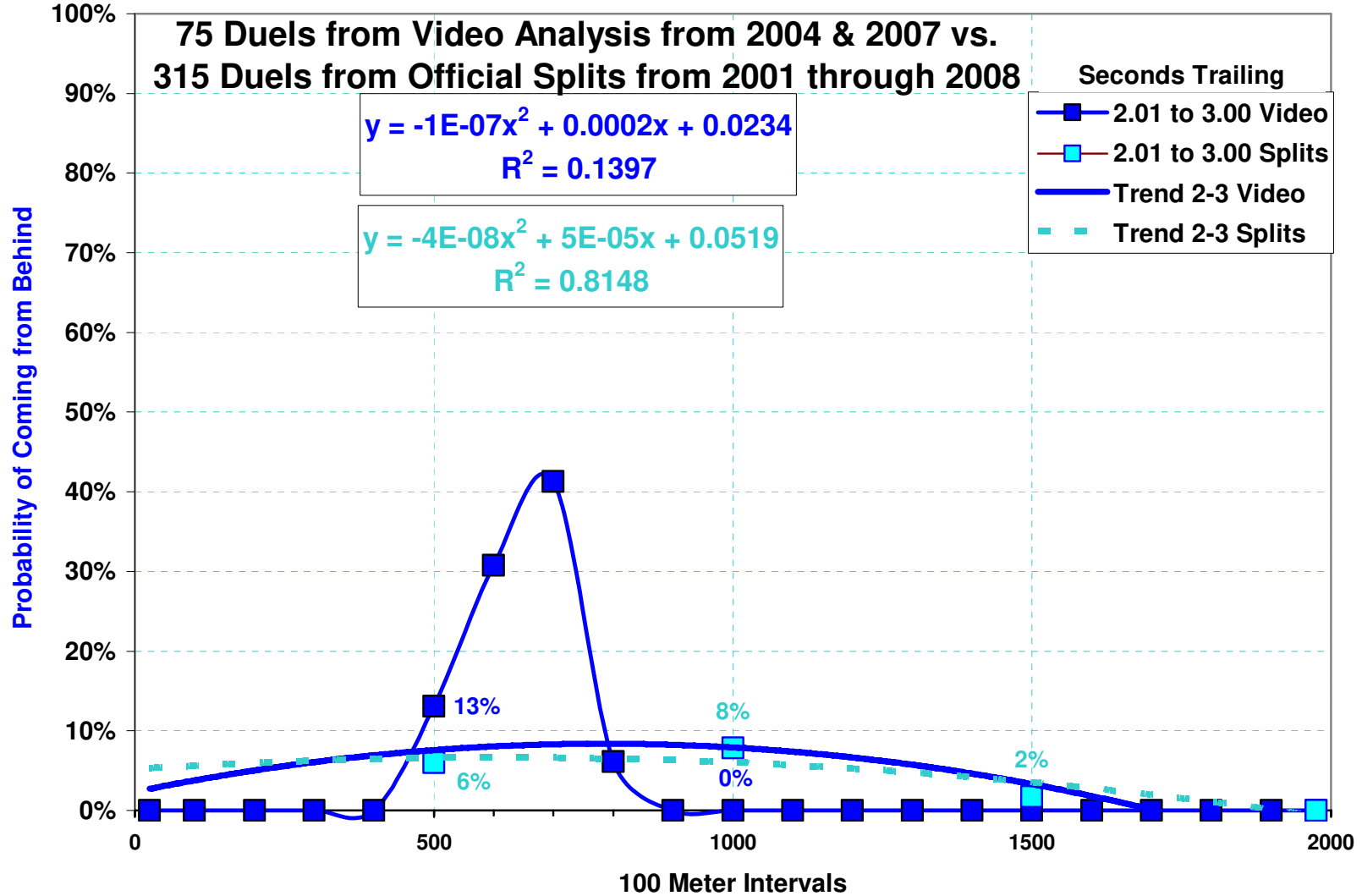
Probability of Winning when Trailing in a Duel



Probability of Winning when Trailing in a Duel



Probability of Winning when Trailing in a Duel



APPENDIX L: PROBABILITY OF WINNING – CONDITIONAL DRIVE ANALYSIS

The probabilities of coming from behind to win a duel can be further differentiated based on the whether or not the trailing crew in a duel is in the process of making a drive. The tables and graphs that follow summarize probabilities based on all observations in comparison to the probabilities for situations in which the trailing crew has improved its positioning over the previous 100 meters of the race.

Crews that are in the process of making a drive show significantly greater odds of winning the duel. This seems intuitive, and this research measures the benefit of making a drive while trailing in a race. Probabilities vary by the magnitude of the lead and position along the course.

For crews with leads of less than 1 second, the overall odds of coming from behind to win improve from 38% to 60% if the trailing crew is in the process of moving on their opponent in a duel. For margins of 1-2 seconds, the drive benefit raises these odds from 20% to 30%. For larger leads of from 2-3 seconds, the drive benefit increases from 3.6% to 5.2%.

Probability of Coming from Behind in a Duel
as a function of whether the trailing crew is making a drive and how strong a drive

		Trailing by 0.01-1.00 seconds in a duel				
Drive Threshold =		Seconds per 100m the Trailing crew is gaining on leader				
Meter Mark	Race Interval	All	0.01	0.05	0.10	0.20
25	1-50	36.8%				
100	51-150	36.2%	55.6%	50.0%	0.0%	
200	151-250	38.9%	55.7%	55.4%	65.1%	81.8%
300	251-350	41.7%	57.1%	58.2%	60.5%	73.3%
400	351-450	41.1%	56.0%	60.6%	58.5%	78.6%
500	451-550	38.8%	50.0%	43.9%	34.5%	38.1%
600	551-650	44.8%	64.1%	67.6%	61.1%	75.0%
700	651-750	45.6%	66.7%	66.3%	62.5%	91.2%
800	751-850	44.2%	68.8%	73.9%	80.6%	100.0%
900	851-950	43.8%	68.0%	78.0%	85.0%	100.0%
1000	951-1050	47.5%	71.4%	76.1%	81.4%	84.5%
1100	1051-1150	49.4%	76.6%	78.9%	77.3%	87.5%
1200	1151-1250	46.2%	80.0%	81.2%	79.6%	83.3%
1300	1251-1350	38.7%	81.0%	89.5%	93.2%	100.0%
1400	1351-1450	31.8%	77.9%	81.7%	90.2%	100.0%
1500	1451-1550	18.8%	50.0%	55.8%	58.6%	14.3%
1600	1551-1650	22.2%	34.5%	41.3%	50.0%	82.4%
1700	1651-1750	23.1%	35.9%	39.3%	55.3%	100.0%
1800	1751-1850	11.8%	18.0%	18.3%	21.6%	10.7%
1900	1851-1950	4.8%	0.0%	0.0%	0.0%	0.0%
1975	1951-2000	0.0%	0.0%	0.0%	0.0%	0.0%
Overall		38.2%	60.3%	63.2%	64.9%	75.6%

Probability of Coming from Behind in a Duel
as a function of whether the trailing crew is making a drive and how strong a drive

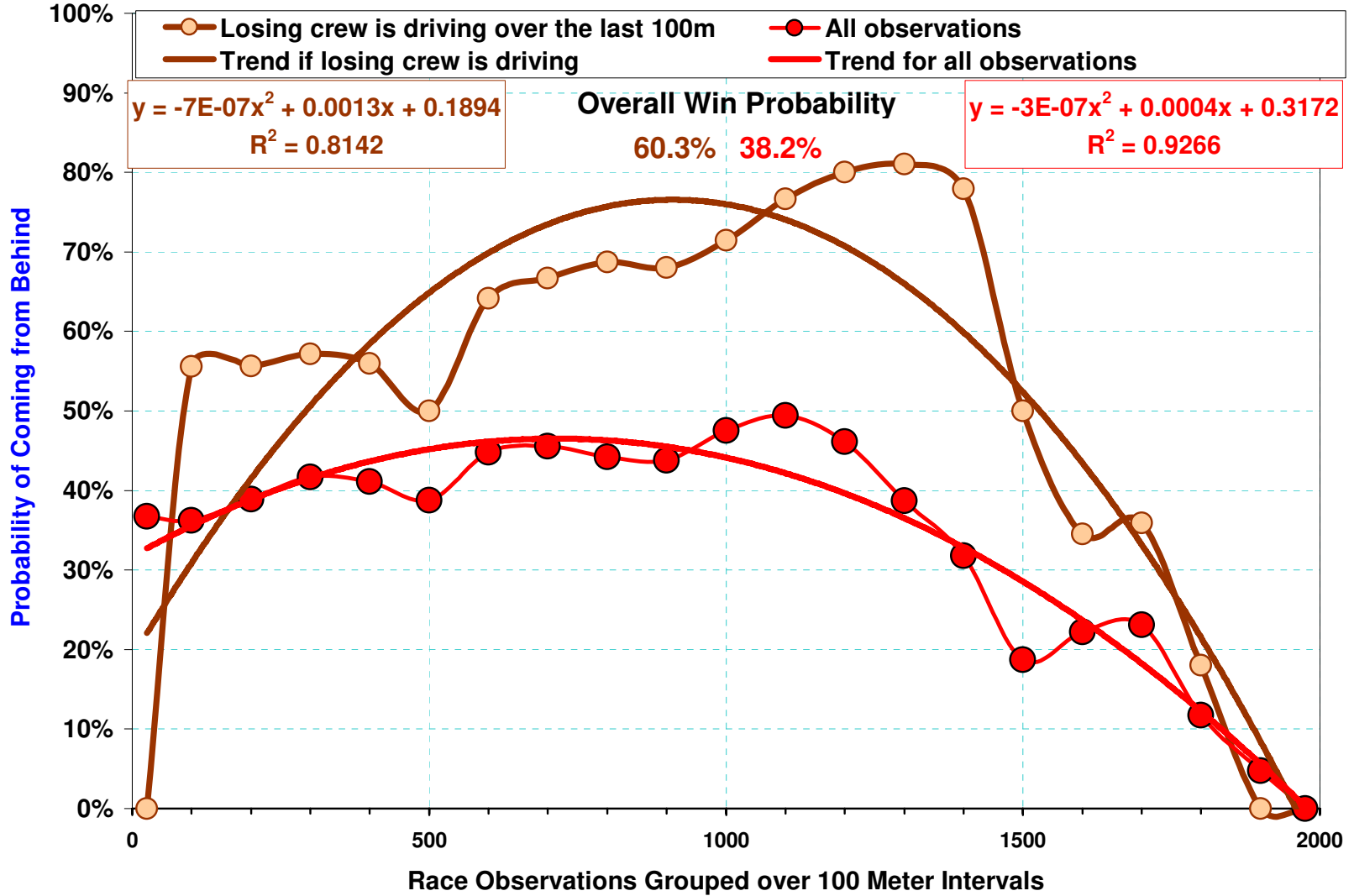
		Trailing by 1.01-2.00 seconds in a duel				
Drive Threshold =		Seconds per 100m the Trailing crew is gaining on leader				
Meter Mark	Race Interval	All	0.01	0.05	0.10	0.20
25	1-50					
100	51-150	0.0%				
200	151-250	21.2%				
300	251-350	27.4%	0.0%	0.0%	0.0%	
400	351-450	39.8%	71.4%	71.4%	100.0%	
500	451-550	47.1%	52.4%	47.1%	54.5%	100.0%
600	551-650	32.1%	71.4%	88.9%	66.7%	
700	651-750	31.3%	67.3%	67.5%	62.5%	64.3%
800	751-850	37.0%	64.1%	64.8%	69.2%	91.5%
900	851-950	32.9%	56.5%	60.8%	70.9%	88.2%
1000	951-1050	20.9%	35.6%	34.5%	38.6%	41.7%
1100	1051-1150	16.7%	41.0%	43.8%	46.9%	50.0%
1200	1151-1250	9.7%	14.0%	17.9%	13.3%	0.0%
1300	1251-1350	5.2%	0.0%	0.0%	0.0%	0.0%
1400	1351-1450	4.7%	0.0%	0.0%	0.0%	0.0%
1500	1451-1550	5.1%	0.0%	0.0%	0.0%	0.0%
1600	1551-1650	6.2%	20.9%	21.1%	29.6%	46.2%
1700	1651-1750	0.0%	0.0%	0.0%	0.0%	0.0%
1800	1751-1850	0.0%	0.0%	0.0%	0.0%	0.0%
1900	1851-1950	0.0%	0.0%	0.0%	0.0%	0.0%
1975	1951-2000	0.0%	0.0%	0.0%	0.0%	0.0%
Overall		19.6%	30.4%	31.7%	35.5%	44.2%

Probability of Coming from Behind in a Duel

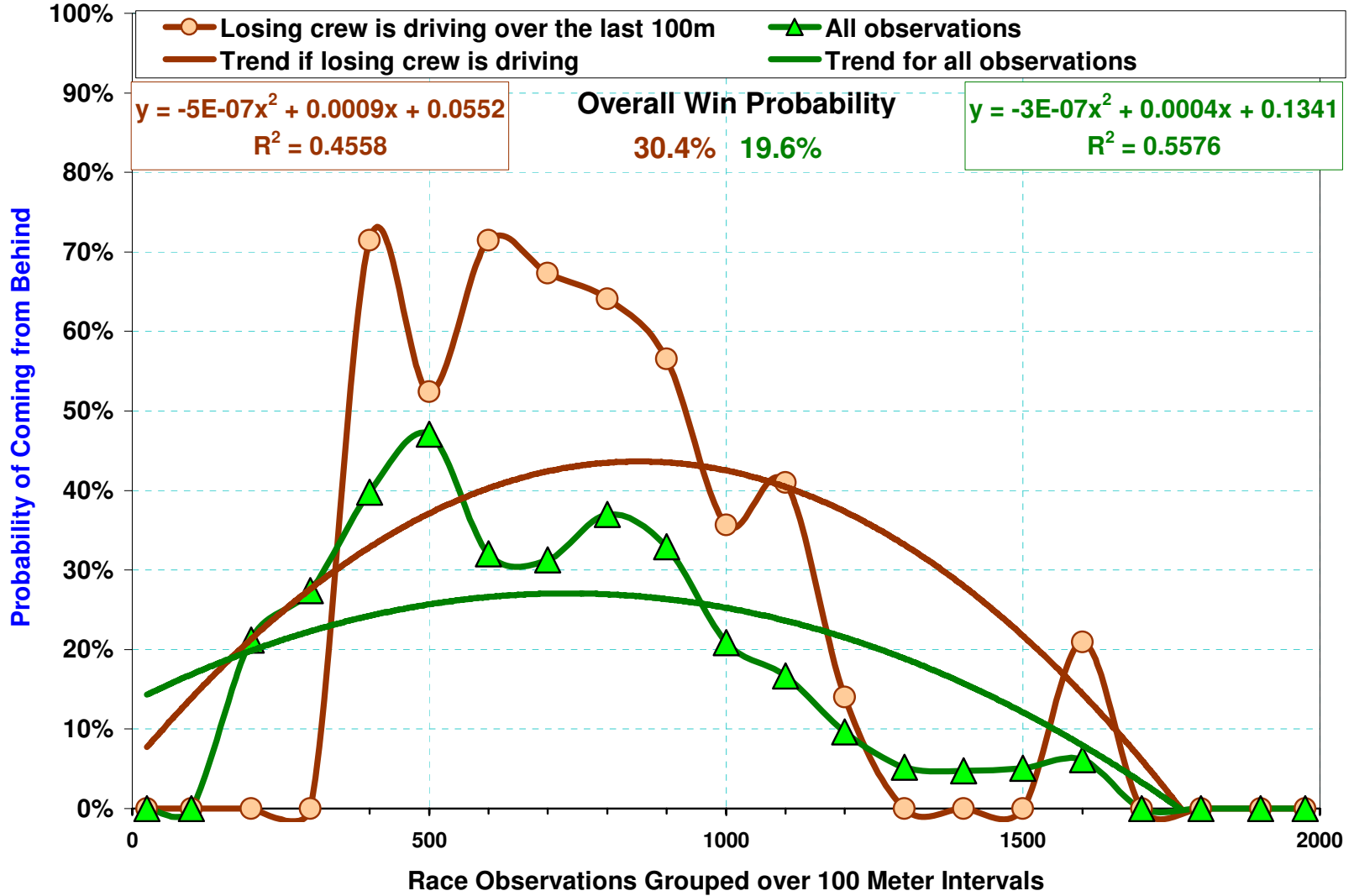
as a function of whether the trailing crew is making a drive and how strong a drive

		Trailing by 2.01-3.00 seconds in a duel				
Drive Threshold =		Seconds per 100m the Trailing crew is gaining on leader				
Meter Mark	Race Interval	All	0.01	0.05	0.10	0.20
25	1-50					
100	51-150					
200	151-250	0.0%				
300	251-350	0.0%				
400	351-450	0.0%				
500	451-550	13.1%				
600	551-650	30.8%	100.0%	100.0%	100.0%	
700	651-750	41.3%	89.5%	94.1%	100.0%	100.0%
800	751-850	6.2%	22.2%	22.2%	22.2%	22.2%
900	851-950	0.0%	0.0%	0.0%	0.0%	0.0%
1000	951-1050	0.0%	0.0%	0.0%	0.0%	0.0%
1100	1051-1150	0.0%	0.0%	0.0%	0.0%	0.0%
1200	1151-1250	0.0%	0.0%	0.0%	0.0%	0.0%
1300	1251-1350	0.0%	0.0%	0.0%	0.0%	0.0%
1400	1351-1450	0.0%	0.0%	0.0%	0.0%	0.0%
1500	1451-1550	0.0%	0.0%	0.0%	0.0%	0.0%
1600	1551-1650	0.0%	0.0%	0.0%	0.0%	0.0%
1700	1651-1750	0.0%	0.0%	0.0%	0.0%	0.0%
1800	1751-1850	0.0%	0.0%	0.0%	0.0%	0.0%
1900	1851-1950	0.0%	0.0%	0.0%	0.0%	0.0%
1975	1951-2000	0.0%	0.0%	0.0%	0.0%	0.0%
Overall		3.6%	5.2%	5.4%	6.6%	7.4%

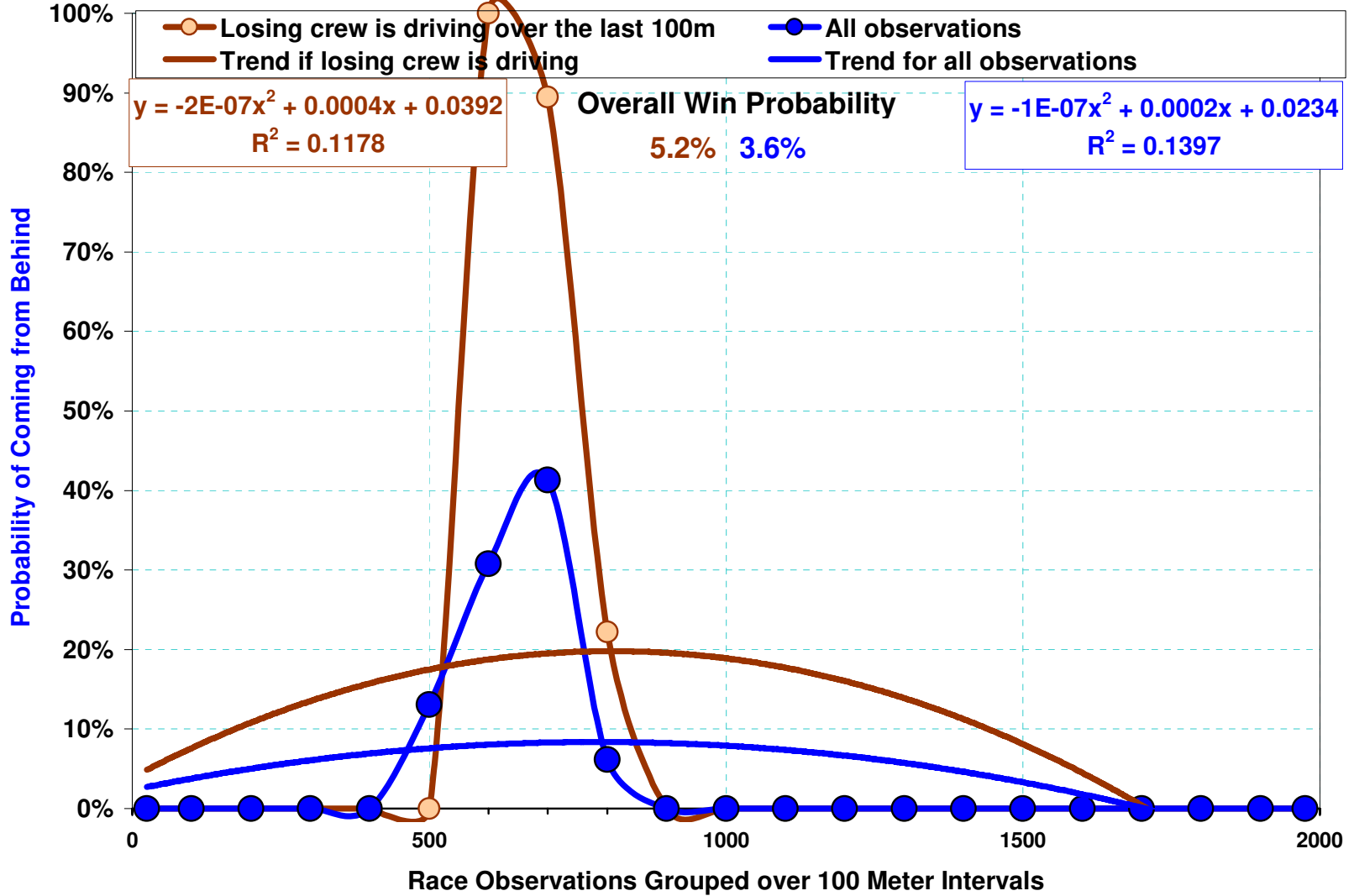
Probability of Winning when Trailing by 0-1 Seconds



Probability of Winning when Trailing by 1-2 Seconds



Probability of Winning when Trailing by 2-3 Seconds



APPENDIX M: IRB EXEMPTION TO STUDY HUMAN SUBJECTS IN A RACE VIDEO

Whenever humans are the subject of research studies, an Institutional Review Board (IRB) may need to be consulted to ensure that the research does not adversely affect the welfare of the people being researched. UCF's IRB was consulted before gathering data from video records. As summarized on the following page, studying human subjects using publicly available world and Olympic championship race video records was judged to pose minimal risk and determined to be "exempt" from IRB rules.



University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901, 407-882-2012 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Notice of Exempt Review Status

From: UCF Institutional Review Board
FWA00000351, Exp. 5/07/10, IRB00001138

To: Jeffrey L. Cornett

Date: June 02, 2008

IRB Number: SBE-08-05645

Study Title: DRIVE-BASED MODELING AND VISUALIZATION OF CREW RACE STRATEGY AND PERFORMANCE

Dear Researcher:

Your research protocol was reviewed by the IRB Vice-chair on 6/1/2008. Per federal regulations, 45 CFR 46.101, your study has been determined to be **minimal risk for human subjects and exempt** from 45 CFR 46 federal regulations and further IRB review or renewal unless you later wish to add the use of identifiers or change the protocol procedures in a way that might increase risk to participants. Before making any changes to your study, call the IRB office to discuss the changes. **A change which incorporates the use of identifiers may mean the study is no longer exempt, thus requiring the submission of a new application to change the classification to expedited if the risk is still minimal.** Please submit the Termination/Final Report form when the study has been completed. All forms may be completed and submitted online at <https://iris.research.ucf.edu>.

The category for which exempt status has been determined for this protocol is as follows:

4. Research involving the collection or study of existing data, documents, records, pathological specimens or diagnostic specimens, if these sources are publicly available or if the information is recorded by the investigator in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects. (*"Existing"* means already collected and/or stored before your study starts, not that collection will occur as part of routine care.)

All data, which may include signed consent form documents, must be retained in a locked file cabinet for a minimum of three years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained on a password-protected computer if electronic information is used. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

On behalf of Tracy Dietz, Ph.D., UCF IRB Chair, this letter is signed by:

Signature applied by Joanne Muratori on 06/02/2008 09:50:01 AM EDT

A handwritten signature in cursive script that reads "Joanne Muratori".

IRB Coordinator

LIST OF REFERENCES

- Anderson, A. (2001). *The Compleat Dr. Rowing*. Groton, MA: Bend the Timber Press.
- Atkinson, W. (2001). *Modeling the dynamics of rowing*. Documentation of the computer model ROWING (unpublished). Retrieved 5/24/2008, from <http://www.atkinsopht.com/row/rowabstr.htm>
- Atkinson, W. (2002). *The moving water fallacy*. Retrieved 5/24/2008, from <http://www.atkinsopht.com/row/movgwatr.htm>
- Atkinson, W. (2004). *Asynchronous rowing*. Retrieved 5/24/2008, from <http://www.atkinsopht.com/row/asynchro.htm>
- Atkinson, W. (2007(1)). *The effect of water temperature*. Retrieved 5/24/2008, from <http://www.atkinsopht.com/row/watrtmp.htm>
- Atkinson, W. (2007(2)). *Shell work; the energy balance of rowing*. Retrieved 5/24/2008, from <http://www.atkinsopht.com/row/shelwork.htm>
- Baltzell, A., & Sedgwick, W. (2000). How elite rowers cope with competitive pressure and expectations to perform. *U.S. National Team Rowing Summary Report for Coaches and Athletes*. A USOC Sport Science and Technology Grant Project.
- Bair Island Aquatic Center. (2008). *Crew, coxswains, boat handling & terms*. Retrieved 5/24/2008, from http://gobair.org/programs/safety_and_care/crew.html#terms
- Bar-Eli, M., Taoz, E., Levy-Kolker, N., & Tennenbaum, G. (1992). Performance quality and behavioral violations as crisis indicators in competition. *International Journal of Sports Psychology*, 23, 325-342.
- Baudouin, A., & Hawkins, D. (2002). A biomechanical review of factors affecting rowing performance. *British Journal of Sports Medicine*, 36(6), 396-402.
- Baudouin, A., & Hawkins, D. (2004). Investigation of biomechanical factors affecting rowing performance. *Journal of Biomechanics*, 37(7), 969-976.
- Barrett, R., & Manning, J. (2004). Relationships between rigging setup, anthropometry, physical capacity, rowing kinematics and rowing performance. *Sports Biomechanics*, 3(2), 221-35.
- Billat, V., Sirvent, P., Py, G., Koralsztein, J., & Mercier, J. (2003). The concept of maximal lactate steady state. A bridge between biochemistry, physiology, and sports science. *Sports Medicine*, 33(6), 407-426.

- Butler, R., Smith, M., & Irwin, I. (1993). The performance profile in practice. *Journal of Applied Sport Psychology*, 5, 48-63.
- Coats, E., Rossiter, H., Day, J., Miura, A., Fukuba, Y., & Whipp, B. (2003). Intensity-dependent tolerance to exercise after attaining V(O₂) max in humans. *Journal of Applied Physiology*, 95(2), 483-90.
- Concept 2 Rowing. (2007). *Weight adjustment frequently asked questions*. 11/11/2007. Retrieved 5/24/2008, from <http://www.concept2.com/us/training/tools/calculators/weightadjfaq.asp>
- Cornett, J. (1974). *Collegiate Crew* (boardgame). Self-published boardgame, 1974.
- Cornett, J. (2005). *A rowing swing model and its application to crew race strategy*. University of Central Florida, unpublished: course EIN 6249 Biomechanics, 4/29/2005, 1-38.
- Cornett, J., Bush, P., & Cummings, N. (2008). An 8-factor model for evaluating crew race performance. *International Journal of Sports Science and Engineering*, 2(3), 169-184.
- Dawson, R., Lockwood, R., Wilson, J., & Freeman, G. (1998). The rowing cycle: Sources of variance and invariance in ergometer and on-the-water performance. *Journal of Motor Behavior*, 30(1), 33-44.
- Farooq, Y. (1992). Five keys to competitive coxing. *American Rowing*, July/August.
- FISA Adaptive. (2008). *The Official World Rowing Web Site - Rowing / Paralympic / Adaptive rowing*. Retrieved 5/24/2008, from <http://www.worldrowing.com/index.php?pageid=17>
- FISA Rules. (2007). *The Official World Rowing Web Site - Publications/Rule Book*. Retrieved 5/24/2008, from <http://www.worldrowing.com/index.php?pageid=71>
- Fukuba, Y., Miura, A., Endo, M., Kan, A., Yanagawa, K., & Whipp, B. (2003). The curvature constant parameter of the power-duration curve for varied-power exercise. *Medical Science Sports Exercise*, 35(8), 1413-8.
- Garland, S. (2005). An analysis of the pacing strategy adopted by elite competitors in 2000m rowing. *British Journal of Sports Medicine*, 39, 39-42.
- Goodfellow, S. (1997). *Can rowing an eight man boat be made more efficient using a sequential stroke?* Retrieved 5/24/2008, from <http://www.goodfelloweb.com/centipede/index.html>
- Hagerman, F. (2005). An update of rowing physiology. *US Olympic Internet Network*. Retrieved 5/24/2008, from <http://www.usrowing.org/itemdisplay.asp?id=1134>

- Hartmann, U., Mader, A., Wasser, K., & Klauer, I. (1993). Peak force, velocity, and power during five and ten maximal rowing ergometer strokes by world class female and male rowers. *International Journal of Sports Medicine*, 14 Supplement 1, S42-45.
- Hartmann, U., & Mader, A. (2005). Rowing physiology. In V. Nolte (Ed.), *Rowing Faster* (pp. 9-23), Champaign, IL: Human Kinetics.
- Hill, H. (2002). Dynamics of coordination within elite rowing crews: evidence from force pattern analysis. *Journal of Sports Sciences*, 20, 101-117.
- Hill, D., Alain, C., & Kennedy, M. (2003). Modeling the relationship between velocity and time to fatigue in rowing. *Medicine and Science in Sports and Exercise*, 35(12), 2098-2105.
- Horsley, C. (1989). Developing attentional skills for rowing. *Australian Institute of Sport, Excel*, 6(1).
- Houston Rowing Club. (1990). Excerpts from "Power Rowing" by Gene Horton. Retrieved 5/24/2008, from <http://members.aol.com/hrcrowing/powerrow1.htm>
- ITN Source. (1931). *Syncopated rowing at the London Rowing Club*, Putney. Gaumont Graphic Newsreel (Reuters). Order Ref: BGT407141226. Retrieved 5/24/2008, from <http://www.itnsource.com/en/Entire-Archive/Search/ShotListDigitised/?ref=/RTV/1931/01/01/BGT407141226.htm&links=ROW&thumb=http://www.itnsource.com/archivedata/Media/RTV/1931/01/01/BGT407141226/92x69-911.jpg&duration=00:01:20>
- Johnson, J. (1989). Tough bodies, tough minds. *American Rowing*, 1989 (May/June), 18-20.
- Jones, C., & Miller, C. (2002). The mechanics and biomechanics of rowing. *Coaching Forum Meeting at York City Rowing Club*, January 20, 2002. Retrieved 5/24/2008, from <http://www.yorkshirerowing.co.uk/biomechanics.htm>
- Joy, J. (2005). Relaxing and focusing on race day. In V. Nolte (Ed.), *Rowing Faster* (pp. 249-259), Champaign, IL: Human Kinetics.
- Keeley, J. (1998). *The Coxswain's Manual*. Coxswain's Locker; 3rd edition.
- Kennedy, M., & Bell, G. (2003). Development of race profiles for the performance of a simulated 2000-m rowing race. *Canadian Journal of Applied Physiology*, 28(4), 536-46.
- Kirschbaum, G. (2003). Glossary. *The Down and Dirty Guide to Coxing*. Self-published by George D. Kirshbaum, Jr., 2nd Edition.

- Klavora, P. (1979). Racing strategy 2: even pace or best performance strategy. *Catch*, 1979(Jan-Feb), 2-3.
- Klavora, P. (1980). Rowing racing strategy: psychological considerations. *The Oarsman*, 12(1), 6-11.
- Kleshnev, V. (1999). Propulsive efficiency of rowing. Canberra, Australia, *Australian Institute of Sport*. Retrieved 5/31/2008, from http://www.biorow.com/Papers_files/1999PropulsEff03.pdf
- Kleshnev, V. (2001(1)). Racing strategy in rowing during Sydney Olympic Games. *Australian Rowing*, 24(1), 20-23.
- Kleshnev, V. (2001(2)). Overview of force application. *Rowing Biomechanics Newsletter*, 1(12). Retrieved 5/31/2008, from http://www.biorow.com/RBN_en/2001RowBiomNews12.pdf
- Kleshnev, V. (2002). Back to basics. *Rowing Biomechanics Newsletter*, 2(11). Retrieved 5/31/2008, from http://www.biorow.com/RBN_en/2002RowBiomNews11.pdf
- Kleshnev, V. (2003). Racing strategies. *Rowing Biomechanics Newsletter*, 3(7). Retrieved 5/31/2008, from http://www.biorow.com/RBN_en/2003RowBiomNews07.pdf
- Kleshnev, V. (2005). Technology for technique improvement. In V. Nolte (Ed.), *Rowing Faster* (pp. 209-225), Champaign, IL: Human Kinetics.
- Kleshnev, V. (2006). *Rowing Biomechanics Newsletter*, 6(65), Appendix 1. Retrieved 5/31/2008, from http://www.biorow.com/RBN_en_2006_files/2006RowBiomNews08.pdf
- Kreiner-Philips, K., & Orlick, T. (1993). Winning after winning: the psychology of ongoing excellence. *The Sport Psychologist*, 7, 31-48.
- MacDonald, S. (1980). Coaching the coxswain. *The Oarsman*, 1980(May-June).
- MacNamee, B. (2004). *Proactive persistent agents: using situational intelligence to create support characters in character-centric computer games*. Doctoral dissertation, University of Dublin, Trinity College, January, 2004. Retrieved 5/31/2008, from <http://www.comp.dit.ie/bmacnamee/papers/Thesis.pdf>
- Maestu, J. (2004). *The perceived recovery-stress state and selected hormonal markers of training stress in highly trained male rowers*. Doctoral dissertation, University of Tartu, Estonia, December 9, 2004. Retrieved 5/31/2008, from <http://www.utlib.ee/ekollekt/diss/dok/2004/b16924332/maestu.pdf>

- Mazzone, T. (1988). Kinesiology of the rowing stroke. *National Strength and Conditioning Association Journal*, 10(2).
- Nideffer, R. (1981). Attentional control training. *The Ethics and Practice of Applied Sport Psychology*. Ithaca, NY: Movement Publications.
- Nolte, V. (1991). Introduction to the biomechanics of rowing. *FISA Coach*, 2(1), 1-6.
- Nolte, V. (2005). *Rowing Faster*. Champaign, IL: Human Kinetics.
- Roth, W. (1991). Physiological-biomechanical aspects of load development and force implementation in rowing. *FISA Coach*, 2(4), 1-9.
- Sanderson, B., & Martindale, W. (1986). Towards optimizing rowing technique. *Medical Science Sports Exercise*, 18(4), 454-468.
- Schwanitz, P. 1991. Applying biomechanics to improving rowing performance. *FISA Coach*, 2(3), 1-7.
- Secher, N. (1993). Physiological and biomechanical aspects of rowing. Implications for training. *Sports Medicine*, 15(1), 24-42.
- Seebrook, J. (2003). Feel No Pain. *The New Yorker*. July 22, 1996.
Retrieved 5/24/2008, from <http://www.booknoise.net/johnseabrook/stories/culture/pain/>
- Seiler, S. (1997). *The physics and physiology of rowing faster: the stroke*. Retrieved 5/24/2008, from <http://home.hia.no/~stephens/ppstroke.htm>
- Seiler, S. (2005). *Physiology of the elite rower*. Retrieved 5/24/2008, from <http://home.hia.no/~stephens/rowphys.htm>
- Smith, R., & Spinks, W. (1995). Discriminant analysis of biomechanical differences between novice, good and elite rowers. *Journal of Sports Sciences*, 13(5), 377-85.
- Sniezek, J., Wilkins, D., & Wadlington, P. (2001). Advanced training for crisis decision making: simulation, critiquing, and immersive interfaces. *Proceedings of the 34th Hawaii International Conference on Systems Science*. Retrieved 5/24/2008, from <http://csdl2.computer.org/comp/proceedings/hicss/2001/0981/03/09813042.pdf>
- Soper, S., & Hume, P. (2004). Towards an ideal rowing technique for performance. *Sports Medicine*, 34(12), 825-848.
- Stowe, W. (2005). *All Together. The Formidable Journey to the Gold with the 1964 Olympic Crew*. Lincoln, NE: iUniverse.

- Tate, R., Tenenbaum, G., & Delpish, A. (2006). Hierarchical linear modeling of individual athlete performance-affect relationships. *Journal of Quantitative Analysis in Sports*, 2(2), 1-27.
- Teti, M., & Nolte, V. (2005). Setting race plans and tactics. In V. Nolte (Ed.), *Rowing Faster* (pp. 237-247), Champaign, IL: Human Kinetics.
- Thompson-Willie, L. (2005). Coxing. In V. Nolte (Ed.), *Rowing Faster* (pp. 261-273), Champaign, IL: Human Kinetics.
- Tuck, E., & Lazauskas, L. (1996). Low drag rowing shells. Presented at the *Third Conference on Mathematics and Computers in Sport*, Bond University, Queensland, Australia, 30 Sept. 1996 - 2nd October 1996. Retrieved 5/24/2008, from <http://www.cyberiad.net/library/rowing/misbond/misbond.htm>
- Tufte, E. (1983). *The Visual Display of Quantitative Information*. Cheshire, CT: Graphics Press.
- US Rowing Nomenclature. (2008). Rowing nomenclature. *US Olympic Internet Network*. Retrieved 5/24/2008, from <http://www.usrowing.org/uploads/docs/5e-1.pdf>
- US Rowing Referee Committee. (2008). *2008 Rules of Rowing*. Princeton, NJ: The United States Rowing Association.
- US Rowing Resource Library. (2008). US Rowing Resource Library. *US Olympic Internet Network*. Retrieved 5/24/2008, from <http://www.usrowing.org/ResourceLibrary/GuidetotheResourceLibrary/index.aspx>.
- Waitley, D., May, J., & Martens, R. (1983). Sports psychology and the elite athlete. Clinics in Sports Medicine, 2(1). In B. Zarins (Ed.), *Symposium on Olympics Sports Medicine*, (pp. 87-99), Philadelphia, PA: W.B. Saunders Co.
- Wing, A., & Woodburn, C. (1995). The coordination and consistency of rowers in a racing eight. *Journal of Sports Sciences*, 13, 187-197.
- Yoshiga, C., & Higuchi, M. (2003). Rowing performance of female and male rowers. *Scandinavian Journal of Medicine and Science in Sports*, 13(5), 317-321.
- Young, C. (1923). *Courtney and Cornell Rowing*. Ithaca, NY: Cornell Publications Printing Company.
- Zatsiorsky, V., & Yakunin, N. (1991). Mechanics and biomechanics of rowing: a review. *International Journal of Sport Biomechanics*, 7, 229-281.

A boat doesn't go forward if each one is rowing their own way.

Swahili proverb