Strategic behaviour in road cycling competitions

Jean-François Mignot

Chapter 10: Strategic behaviour in road cycling competitions

Jean-François Mignot

Introduction

Cycling is arguably one of the hardest sports, requiring tremendous amounts of strength, endurance, resistance to pain and courage. However, as reputed specialists of the Tour de France noted, "*God knows the Tour is also a matter of intelligence and tactics*" (Chany and Cazeneuve 2003). Why is there strategy, not just brute force, in cycling competitions? What are the recurring strategic interactions among riders? And what can economists learn from riders' behaviors?

Professional sport is an ideal setting to study strategy. First, sport usually provides well-structured and easy-to-model situations: they include a small number of players, each player has clearly identifiable opportunities of action, and each action includes easily measurable payoffs. Second, professional athletes are specialists in their sport's strategy and so they should, given they are playing for high stakes. Moreover, cycling may be one of the most strategically interesting sports, hence it nickname "chess on wheels" (Harper 2012). Much more than in, for example, swimming or athletics (especially in the case of short-distance running, or throwing and jumping events), professional riders' performances crucially depend on their interactions with other riders. Most of the interactions between riders are not pure confrontation, zero-sum games, as is the case in boxing, fencing, martial arts or tennis. Although riders are basically competing for a fixed-sum prize pool, the games they play are usually not constant-sum, if only because "*while there might always be the same number of winners and losers, it can be less costly for everyone to play the game*" (Dixit and Nalebuff 2008). In addition, in cycling two rival riders may lawfully ally against some third rider, while such three-player interactions do not exist in football, basketball or soccer. And cycling being an individual sport run among teams opens up opportunities of strategic behavior both within and between teams.

This chapter first provides an overview on the main reasons why bicycle races are strategic and not just a mere display of brute force. Next, several game-theory analyses of strategic interactions between riders are presented: attack timing strategy (section 2), cooperation and noncooperation in breakaways and in the peloton (section 3), three-player interactions (section 4) and sprint strategy (section 5). It is founded on examples of strategic interactions between riders that occurred in the Tour de France (Chany and Cazeneuve 2003; McGann and McGann 2006, 2008), the Giro d'Italia (McGann and McGann 2011, 2012), the Vuelta a España (Fallon and Bell 2013) and other races (Chany and Penot 1997; McKay 2012).

1. Why is there strategy, not just brute force, in road cycling competitions?

Cycling involves strategy, i.e. each rider's best action depends on other riders' actions. A fundamental reason why this is the case has to do with air resistance, which gives riders the opportunity to accept or to refuse to cooperate. The fact that road races are run in a team format only intensifies this strategic dimension.

1.1. Air resistance, drafting and crosswind

"*In competitive cycling on the flat, air resistance is by far the greatest force opposing the forward motion of a cyclist. Air resistance can be dramatically reduced by riding in the slipstream of another rider or vehicle. The following rider will then enjoy the low pressure area behind the lead rider*" (Olds 1998). "Drafting" or "slipstreaming," i.e. riding in the shelter of another cyclist or group of cyclists and staying out of the wind, indeed confers a very substantial "second-mover advantage": the back rider is able to reduce his effort by up to 40% (Dilger and Geyer 2009). Hence spectators of road races can see that while at the front of the main group riders are spending substantial amounts of energy to maintain a high speed, certain riders at the back are freewheeling. More generally, the average rider in the peloton uses his energy more efficiently than the average rider in a breakaway, let alone a solo rider. As a consequence, a rider who somehow manages to spend relatively little energy may win a race against a stronger opponent who was unable to conserve as much energy. Therefore two common strategies are available to riders: "cooperation," i.e. taking turns at the front and letting other riders ride in one's slipstream (at least for some time), and "defection," i.e. refusing to ride at the front. Most importantly, drafting enables riders to help each other and gain from that mutual help. Two riders may "take pulls," i.e. take turns shielding each other from the wind. For instance, on the 11th stage of the 1985 Tour de France, French champion Bernard Hinault broke away from the peloton with Colombian climber Luis Herrera. While Hinault shielded Herrera from the wind on the flat, Herrera shielded Hinault in the mountains, enabling Hinault to cushion his general classification jersey and Herrera to cushion his king-of-the-mountains jersey and win the stage. Alternatively, a rider may draft as much as possible and shirk to gain from unilateral help.

Air resistance also varies with certain parameters in ways which help us to understand bicycle racing. First, air resistance is higher at a higher speed, which implies that drafting is more advantageous (and breakaways are less likely to succeed) on the flat than in the mountain. Because a straight and dry road increases speed, drafting is more advantageous in these conditions than on a winding, wet road. Drafting is not particularly advantageous in descents, though, because riding closely behind another rider prohibitively increases the risk of a serious accident. Second, air resistance is higher in the presence of headwind, so drafting is also more advantageous in the presence of headwind. By contrast, crosswinds make it difficult to draft in the peloton, which is why attacks occur more often when there is crosswind. Third, as we learn from physics, when an object's linear dimensions increase by one unit, areas increase by this unit *squared* and volumes increase by this unit *cubed*. Consequently, when cyclists are on the flat and they must spend energy to overcome the air resistance of their body surface area, taller cyclists have a lower frontal drag (body area) relative to their muscular mass (body volume), which makes them more efficient than shorter cyclists (Prinz and Wicker 2012). By contrast, when cyclists are in the mountain and they must spend energy to overcome the gravity of their mass, shorter cyclists have a lower body mass (body volume) relative to their lungs and muscles' capillary surface (body area) and aerobic power output, which makes them more efficient than taller cyclists (Prinz and Wicker 2012). This is the main reason why certain riders are relatively stronger on the flat ("*rouleur*" in French, "*passista*" in Italian) while others are better in the mountain ("*grimpeur*," "*scalatore*"). Air resistance is also lower at a higher altitude, which is why several world hour records were beaten in Mexico City.

When the peloton is on a straight road heading north at a certain speed and a crosswind blows from the west, each rider faces air resistance coming from the northwest, a combination of pure air resistance coming from the north and actual wind coming from the west. In such a situation a rider will usually not ride right behind his predecessor (as if there were no wind or only wind coming from the north or south) but instead he will position slightly to the right of his predecessor so that the latter shields him from the overall air resistance coming from the northwest. Thus the peloton will form a diagonal "*echelon*" on the road, which reduces the share of the peloton's riders who can draft and spare energy. Additionally, when teammates form an echelon they will laterally position on the road so that the rider at the back of the group is as close as possible to the right-side gutter or "*bordure*" because this prevents other teams' riders from benefiting from the back rider's shield against the air resistance coming from the northwest. In other words, teammates will exploit the fact that drafting is a club good, i.e. a non-rival but excludable good. For example, in the 13th stage of the 2013 Tour de France, this bordure strategy helped several contenders for the general classification gain time on race favorite Christopher Froome.

1.2. Cycling races as strategic individual and team competitions

Road races are individual competitions in several senses. The general classification's winner is an individual person. Among 'grand tours', only the 1912 Giro was raced and won by teams, not individuals. Many riders and especially team leaders exclusively pursue their individual objectives and most cyclists also have a personal coach to monitor their physiological preparation, but they have no team coach (Larson & Maxcy, 2013; for more on coaching, see chapter 8). Certain stages such as individual time trial stages are even strictly individual competitions. However, road races may also be considered team competitions. The team general classification's winner is a team (the team's time is calculated on the basis of its best three riders per stage), and certain stages such as team time trials are strictly team competitions (the team's time is that of usually the fifth quickest teammate). Most importantly, many riders do not race for themselves but for their team leader. Within each team, riders called "*domestiques*" (servants in French) or "*gregari*" (in Italian) are paid to help their leader, thus making for a more exciting if less egalitarian show. The fact that road races are team competitions opens up opportunities for strategic interactions, i.e. cooperation and defection, both between and within teams. Within teams, the diffusion of two-way radios between the team director and his riders has since the 1990s also increased the importance of team directors' strategic decisions (Larson & Maxcy, 2014).

As a result, a rider's individual performance is not determined by his individual characteristics only (a lower body mass index, better past performance, etc.) but also by team characteristics such as his teammates' performance and experience and his relative performance in the team. This is because team leaders profit from their domestiques' help. Thus, teams may be more efficient or less efficient in transforming individual riders' performances into team performance (Rogge et al. 2012). Even the great Luxembourg climber Charly Gaul was heavily handicapped by the fact that his "national" team included riders from various countries who were unwilling to sacrifice for him and reciprocally, until 1956, he was unwilling to share his Tour prizes with them. Since the 1970s, domestiques actually sacrifice their own chances more and more to help their team leader, as proven by the fact that in the Tour the increase in performance inequality among riders is entirely due to an increase in performance inequalities within, not between teams (Candelon and Dupuy 2010).

Road cycling competitions are strategic because riders nearly always start together in a bunch, subdivided into teams, which enables them to draft each other and otherwise cooperate within and across teams. One-day races on a closed circuit (e.g. World Championships) or from one city to another (e.g. Paris-Roubaix) allow drafting and include an important strategic dimension: when should a rider draft or attack, when and with whom should he ally, and to what extent should he cooperate with those allies? Stage races (e.g. the Tour de France) include all these strategic questions but also require that riders formulate and sometimes modify a race strategy over about twenty stages. As Prinz and Wicker (2012) claim: "*a promising avenue for rather unsuccessful teams would be to understand the principles of game theory. Certainly, given the nature of a repeated game (multiple stages), future research of the determinants of cycling success should implement a more game theoretical approach*".

In addition, road races are run among teams, and possibly under crosswind, which still increases their strategic dimension.

The only non-strategic road cycling competitions are time trials. Although they must use aerodynamic equipment and position themselves on their bicycle to minimize air resistance, they cannot draft or otherwise cooperate, which means the strongest rider wins. However, the idea that road time trials do not include any strategic element may be disputed. First, in time trials in stage races, where riders start off in the general classification's reverse order (the last rider starts first and the leader starts last), starting off later gives informational advantages. Starting later than teammates allows a rider to gather information on the route and adjust, for example, his equipment or his gear, and starting later than a rival allows a rider to know how much time he needs to gain or not lose to reach a given goal, which may motivate him to gain some amount of time or allow him not to take unnecessary risks. Second, starting off earlier may give a psychological advantage. A rider may try to start very quickly to demoralize the rivals he knows will realize they initially lose time on him. Third, a rider may be better off not spending all his energy and deliberately losing time in a time trial if that makes him less threatening on the general classification and thus induces leaders to let him break away and win later stages or secondary prizes such as the king-of-the-mountains jersey. One of the greatest time trialist of the 1950s and 1960s, Jacques Anquetil, said: "*I keep telling journalists my secret: in a time trial you have to start flat out, finish flat out and take a breather in between [...]. Obviously that's not what I do but I still keep telling that's what I do. All my rivals end up trying*" (Fournel 2012).

1.3. Game theory in road cycling

This chapter uses game theory to analyze interdependent situations (games) in which each rider (player) has to decide which action (strategy) to choose knowing that his best action depends on others' actions, and also knowing that all riders face a similar situation (Aumann and Hart 2002). A rider's choice of a strategy is then based on his preferences over his strategies' outcomes (payoffs), which may themselves be the result of their will to maximize their average placing, their victories or their total lifetime income, including both fixed wages and cash prizes (see text box "What are riders chasing after?"). Game theory helps analyze riders' strategic behaviors given their preferences. The games riders play are solved by finding their Nash equilibrium, i.e. a combination of strategies which are *mutual best responses* to each other, so that it is not in any rider's strict interest to unilaterally change strategy. An example of such mutual best response is given by Rik Van Steenbergen's victory in the 1952 Paris-Roubaix, when he out-sprinted Fausto Coppi. In the last 20 km, Coppi repeatedly attacked, but each time Van Steenbergen caught up to him. On Coppi's last attack, Van Steenbergen lost 15 meters, but he was finally able to catch up again. After his victory, Van Steenbergen declared that, had Coppi attacked one more time — only once — he could not have followed him. When Coppi heard about Van Steenbergen's declaration, he said: "*Had I had a bit of energy left, I would have attacked, indeed*" (Chany and Penot 1997).

What are riders chasing after?

Few riders can hope to win a race or otherwise make a name for themselves, let alone gain a legendary record. As professionals, most riders aim at maximizing their income or, to some extent, their prestige. Many riders would not participate in cycling races or would quit if little or no money was involved. In 1913, after French champion Octave Lapize quit the Tour, he explained: "*The Tour is not a good deal for me! In the team I am the only one fighting to make money and some of my teammates are demanding more money than they should. If I win the Tour, which is easier said than done, I will hardly earn 7,000 francs. Track contracts [i.e. money given by velodromes to have riders participate in track races] will earn me much more*" (Chany and Cazeneuve 2003). After Lapize quit, his teammates could not hope to earn any more money so they too quit the race. Similarly, when in the 1960s French champion Jacques Anquetil was asked by a journalist if he would be willing to race for a medal alone, and not money, he said: "*No. Cycling is too hard a sport for me to be willing to race for a medal*." In 1965, Jacques Anquetil deliberately chose not to participate in the Tour because the public was tired of his all-too-frequent and predictable victories. He said: "*If I win the Tour de France a sixth time my criterium contracts will not get more rewarding. However if I do not win they will definitely become less rewarding. Don't count on me!*" (Chany and Cazeneuve 2003)

More generally, professional cycling is definitely a sport in which "money talks." In the 1962 Vuelta, once it turned out that Rudi Altig had a better chance of winning than his team leader Jacques Anquetil, Jean-Claude Annaert spoke for all of [the teammates]: "*We'll help Altig if he shares the winnings in the same way Jacques [Anquetil] was going to. If not, we stand to lose more than a million francs, and he can hang out to dry in the days that remain*" (Fallon and Bell 2013). Altig promised to share his prizes, his team supported him and they won. In the 1975 Giro, while Roger De Vlaeminck had already won four stages, a journalist from the *Gazzetta dello Sport*, Rino Negri, asked him if he would do better than Merckx. ""*That means seven stage wins. No, it's impossible for me*," demurred De Vlaeminck. "*100,000 Lire?*" persisted Negri. De Vlaeminck shook his hand and the bet was on. (McGann and McGann 2012). De Vlaeminck finally won seven stages and his bet.

2. Attack timing strategy: when to attack?

To win, a rider has to decide on what portion of the race to attack. "*Attacking*" means accelerating swiftly in order to break away (i.e. to prevent certain riders from drafting), gain time on the peloton and possibly win. Attacking is costly, though. First, because an attack has to be abrupt or it will not enable the attacker to drop his opponents, attacking requires considerable energy. For any given average speed of a race, attacking and then riding slower requires more overall energy than riding at constant speed. Second, once the opponents have been dropped, keeping them at a distance also requires considerable energy if, as is usually the case, there are fewer riders in the breakaway than in the peloton, which means fewer opportunities of drafting. Consequently, riders who attack too hard or too often risk what is called "*meeting the man with the hammer*" ("*défaillance*" or "*fringale*" in French) and losing a considerable amount of time, whether on the day of the attack or, in stage races, in the following days. This is why no rider can afford to attack or ride in the wind all the time. Team directors, leaders and other riders must therefore decide when to attack and forgo the benefits of drafting, both on flat and mountain stages. And in stage races, riders must also decide whether to attack early or late in the race. These questions are somewhat related to each other, however, because organizers usually position flat stages in the early part of a stage race and save mountain stages, where time gaps are the greatest, for the later part to keep up suspense for as long as possible (Van Reeth 2013).

2.1. Flat-stage strategy: when do you attack to win the stage?

On a flat stage, riders have to fight against air resistance, which strongly disadvantages breakaways relative to the peloton. In this context, a rider who hopes to win a stage has two basic options. He may stay in the peloton, draft for most of the stage and spend his remaining energy to try to beat the other riders in the final sprint. These "sprinters" may thus win stages and the sprinter's jersey, but this strategy does not allow them to gain time on the peloton (for more on sprint strategy, see section 5). Alternatively, a rider may spend his energy to try to break away and keep the peloton at a distance until the stage arrival. Successful breakaway riders may thus gain some time on the peloton and one of them would also win the stage. Riders concerned more about the overall standings could choose to employ these two strategies as well, either to save energy and prevent time losses in the first case, or to try to gain a time advantage through a breakaway's success in the second case. So if a rider were to employ the latter strategy and attempt to break away on the flat, when and with whom should they attack?

As a rider decides when to attack he faces a dilemma. If he attacks too early, he will get exhausted sooner and he will end up easily caught up by the peloton. And if he attacks too late, the peloton will make it much harder for him to break away in the first place because more teams with a sprinter will not want to lose the opportunity of the stage finishing in a sprint. If a rider attacks at the very end of the stage, sprinters themselves will easily beat him. If one were to compute the likelihood of breakaway success for each of the stage's kilometers at which a rider can launch his attack, the resulting curve would likely be inverted-U-shaped. In the first part of the stage, the peloton lets most attackers break away. However, out of exhaustion or because of a lack of cooperation between the breakaway riders (see section 3), these early attacks usually fail to keep the peloton at distance until the stage finish. Later in the stage, where the increased proximity to the finish improves a breakaway's chances of survival, the peloton becomes increasingly more reluctant to let attackers break away. Late attacks often do not even succeed at breaking away for more than a few minutes. Overall, riders should draft in the peloton until they feel that in the remaining kilometers the peloton will not let them break away any more. At the last possible moment they should preempt the peloton's decision and attack to escape the peloton using that latest available opportunity.

This interaction has the structure of a "duel" (Polak 2008). A duel is a zero-sum sequential-move game where two gunfighters, each with a one-bullet gun in their hands, stand at some distance from each other. Each in turn then chooses whether to make a step towards the other or fire. Gunfighters know each other's probability of hitting at every distance. The probability of hitting increases as they get closer and closer. If a fighter fires and hits, he wins (+1) and the other loses (-1). But if he fires and misses, he loses because the other will then get as close as he can and will fire and hit with certainty. When should they fire if it is in each fighter's interest not to fire too early (higher risk to miss) or too late (the other fighter might decide to shoot first)? The only Nash equilibrium (i.e. the combination of mutual best responses) of this game shows that it is in each gunfighter's interest to fire precisely at the moment when his likelihood of hitting by firing now exceeds his likelihood of not being hit later, i.e. when his chance of success equals his rival's risk of failure. This situation is similar to a market where each of two firms has to decide when to launch its new product: not too early or it will not sell, not too late or the other firm will have scooped the market. Each will launch its product once delaying its decision starts reducing its chances of winning the whole market.

Thus a rider should attack, perhaps in cooperation with other riders, following a similar strategy: right before the moment when delaying the attack starts reducing his chances of winning the stage. The peloton may "wake up" and start chasing too late when riders are tired (e.g. the day after a hard mountain stage or right after the peloton caught up on a previous breakaway) or when they prefer to save themselves for future stages (e.g. the day before a hard mountain stage). Riders should also attack when certain teams will not cooperate to chase down breakaways, e.g. when these teams figure in the breakaway, when the breakaway does not jeopardize any team's leadership jersey, or when general classification leaders are waiting for each other to attack first. Optimal attack timing also depends on various stage parameters. In the presence of crosswinds or on winding, rough or wet roads, the peloton's air resistance advantage is less pronounced, so the peloton will prevent riders from breaking away from an earlier time point and riders should attack earlier.

When deciding his attack timing, a rider may also try to profit from the peloton's possible off-guard moments. A rider's reasoning may go as follows: if the peloton is going to be more watchful before the next bend, I should attack right after it, and vice versa (i.e. anti-coordinate). At the same time, the peloton may be willing to be especially watchful whenever the rider who seems willing to attack may believe that it is least watchful (i.e. coordinate). Thus, when a rider is deciding when or where to attack, he is effectively playing a “game of matching pennies” (or “cat and mouse”) with the peloton (table 10.1).

Table 10.1 Attack timing strategy as a “Game of matching pennies”

		Attacker	
		Attack early	Attack late
Opponent or peloton	Be on watch early	4 ; 0	0 ; 4
	Be on watch late	0 ; 4	4 ; 0

In this “strategic form” payoff matrix each row is one of the opponent’s two choices and similarly each column is one of the attacker’s two choices. In each cell at the intersection of these choices (or strategies) one finds two numbers. The first represents the opponent’s utility level, the second represents the attacker’s utility level. These cardinal payoffs go from 1 (least preferred outcome) to 4 (most preferred outcome).

The “game of matching pennies” (like its three-strategy analog “rock, paper, scissors”) is a zero-sum de-coordination game with no Nash equilibrium in pure strategies but one equilibrium in mixed strategies. Each player mixes his play by choosing one of two strategies with 0.5 probability. In such a game, a player cannot “surprise” the other without surprising himself, i.e. he must randomize his behavior. In professional road cycling, an attack is most likely to be unexpected when the rider is attacking from the back of an opponent or when the opponent is not on the watch, e.g. when he is talking to his teammates or team director. An opponent may also not be able to follow an attack if he is in the middle of the peloton or faces mechanical problems. In the 11^{th} stage of the 1949 Giro, Fausto Coppi attacked Gino Bartali while he was eating and was about to stop to change a wheel. In the 7^{th} stage of the 1974 Tour, as soon as Eddy Merckx heard about Gerben Karstens’ tire puncture he attacked and won the stage. Riders are also vulnerable right after they change to a higher gear, because at that time swiftly accelerating is harder. Opponents may profit from this to attack very hard using lower gears. More generally, as the “game of matching pennies” shows, the timing of a surprise attack must be randomized. Great champions such as Eddy Merckx and Bernard Hinault were known to be masters of psychology because they could attack at any time. Tennis players also play a “game of matching pennies”: the server may serve to the right or left of the receiver, and the receiver has to anticipate left or right. The mixed-strategy Nash equilibrium of this game indicates that servers should equalize their probabilities of winning by serving to the right or left, and this is precisely what champions do (Walker and Wooders

2001. For similar results about penalty kicks in soccer we refer to Chiappori et al. 2002 and Palacios-Huerta 2003.

2.2. Mountain-stage strategy: when do you attack to win the stage?

Successful breakaways on the flat are rare. They require optimal attack timing and, as we will show in section 3, cooperation among the breakaway riders and non-cooperation among the peloton. Furthermore, even those breakaways that succeed generally win the stage with small time gains. Attacking on the flat thus serves the purpose of winning stages more than gaining time. Mountain stages, by contrast, enable certain riders to gain considerable amounts of time over their competitors.

On a mountain stage, especially with a hilltop finish, riders have to fight against the gravity of their mass more than against air resistance, which means breakaway riders do not face as strong a disadvantage relative to the peloton as on a flat stage. Therefore, strategies are not the same in mountain stages as in flat stages. The stronger a rider feels and the lower his risk of getting completely exhausted, the earlier he should attack to give himself more time to build a big gap on the peloton. In the 18th stage of the 2011 Tour, a hard mountain stage with three consecutive climbs and a hilltop finish, fourth-placed Andy Schleck broke away from his rivals at 62 kilometers from the finish. He won the stage and took enough time on his rivals to move up to second place overall. By contrast, while attacking late is less costly in terms of energy, it may not allow a rider to build big time gaps by the finish line. A common strategy for the general classification contenders therefore consists of attacking in the later part of each mountain stage, which enables them to both gain some time on opponents while taking few risks with overall energy expenditure. In the 8th stage of the 2013 Tour, Christopher Froome attacked a few kilometers away from the finish of the last climb to test his opponents once they were tired while avoiding risks of blowing up from an extended sortie.

Deciding to join the right attack, or to join an attack at the right time in the mountains, may gain a rider the yellow jersey. For example, in the 14th stage of the 1976 Tour, second-placed Lucien van Impe was ordered by his team director Cyrille Guimard to attack early. Meanwhile, third-placed Joop Zoetemelk stayed in leader Raymond Delisle's slipstream, believing that in the unlikely event Van Impe gained time on both of them it is the leader who would have to chase him down. Indeed, when a breakaway threatens the leader, it usually is in his competitors' interest to draft him because in professional road cycling there is an unwritten law that the leader should do the work of chasing down the breakaway. However, Delisle turned out to be incapable of chasing down Van Impe and Zoetemelk started chasing

Van Impe too late. As a result, Van Impe gained considerable time on both Delisle and Zoetemelk, became the general classification leader, and ultimately won the Tour.

2.3. Stage race strategy: on which stage(s) do you attack to win the race?

Because no rider can afford to keep attacking, general classification riders save themselves on most stages and focus their effort on a few key stages where they can widen the gap the most. Riders may even win a 'grand tour' without any stage victories at all, as did Firmin Lambot (1922), Roger Walkowiak (1956) and Alberto Contador (2010, before being disqualified for doping) in the Tour, Carlo Oriani (1913) and Franco Balmamion (1962) in the Giro, as well as Ángel Casero (2001) and Alejandro Valverde (2009) in the Vuelta.

On which stages can riders gain time and the race? The peloton's advantage against air resistance is the highest on the flat stages, so riders aiming at the general classification are better off not attacking on the flat. Similarly there is no need to use too much energy or take too many risks on the prologue, which is too short to make significant time differences. After the prologue of the 1983 Vuelta, Bernard Hinault explained why he did not take too many risks: "*With 3,000 km left to dispute, it was absurd to risk everything in the first six. I know when I'll put on the leader's jersey, and as long as I don't have an accident, no one will take it off me*" (Fallon and Bell 2013). In 1995, while the prologue of the Tour was raced on a rainy day and the road was wet, Miguel Indurain chose to not take risks and he did not win the prologue. Those who spend maximum energy or take risks in the prologue are riders who have no chance other than the prologue to get the leader's jersey, or riders who want to show they should become the team leader.

For any given energy expense, a rider can gain more time in mountain stages or time trials. A climber's strategy consists in limiting his losses in time trials and attacking in the mountains. Although, as explained earlier, there usually is no strategy in time trial stages (each rider faces the wind and goes as fast as he can), a time trialist's strategy on a stage race consists in gaining time in early time trials and then drafting his opponents as much as possible when they attack in the mountains. This was Jacques Anquetil's "economical" strategy, which was radicalized by Miguel Indurain, a five-time Tour de France winner who did not win a single stage of the Tours he won, except time trials. It should also be noted that since the 1970s, as technological advances improved time trial performances more than mountain performances, time trials may have become relatively more determinant of victory than before. One common point between climbers' and time trialists' strategies is their use of what game theorists call "backward induction" in sequential-move games. If a rider knows he can gain at least x

minutes on his opponent in a late mountain or time trial stage, he need not unnecessarily spend energy in early stages to catch up on a delay which is inferior to *x*.

When deciding on in what stages to attack, a rider has multiple reasons to believe that "good things come to those who wait." Efforts in later stagers tend to be more profitable in terms of time gained. First, in a 'grand tour' after one or two out of three weeks, some riders have abandoned the race due to crashes or mechanical misfortune. A rider can thus focus his attacks on those remaining opponents who compete for the win. Second, late in the race, teams get weaker and riders get tired, making it easier to drop leaders from competing teams. Third, attacking right before the end of the stage race allows a rider to make extremely intense efforts without having to worry about the risk of blowing up in the following days. This allows avoiding "Pyrrhic victories", i.e. stage wins that make you gain time but leave you so exhausted that the day after you lose everything. Fourth, because defending the leader's jersey is costly to the whole team since you have to fight against many teams at a time and catch up on the breakaways, the later you take hold of the jersey the less costly it is to keep it until the end of the race. This is why certain teams aiming at the overall win may prefer not to lead too early, for fear of weakening the team and being unable to protect the leader's jersey until the very end. In 1999, after Lance Armstrong won the Tour prologue, U.S. Postal team director Johan Bruyneel said: "*We will not do everything in our power to keep it. There is no reason for Lance to take unnecessary risks in the coming days. Our first objective is the Metz time trial [i.e. the 8th stage]*." This is how from the 2nd to the 7th stage the U.S. Postal team 'gave' the leader's jersey to the Casino team and subsequently let sprinter teams chase down breakaways and otherwise control the race. At the same time, Lance Armstrong was also saved for almost a week from the time consuming ceremonial obligations that go along with wearing the yellow jersey. Such extra rest is very welcome at the beginning of a three week stage race.

These strategic considerations are all the more important since once a rider has taken the lead, his challengers may find it difficult to join forces and attack him. Although the leader's challengers would collectively be better off coordinating their attacks against him, each may prefer to wait and draft the first attackers, and attack only once the leader has been exhausted by repeated attacks. This leads to the suboptimal situation where no one starts attacking the leader. However, could not the leader's challengers attack him simultaneously? While this is possible, the runner-up may be afraid to cooperate with the third-placed rider for fear of turning out to be weaker and losing his second place. Or the third-placed rider may fear exhausting himself and losing his third place on a following day. In other words, if followers cannot trust each other to attack the leader but not attack each other, each may prefer to secure an honorable placing. In 1961, Tour organizer Jacques Goddet called riders who did not challenge Jacques Anquetil's lead "dwarfs of the road". They may have been dwarfs of the road, but it is no surprise none was willing to take the risk of losing everything to have a slight chance of winning in the unlikely event all challengers took the risk to coordinate their attacks. When his challengers are playing against each other this way, the leader may profit from "social dilemmas", known in game theory as prisoner's dilemmas and assurance games (Kollock 1998).

The fact it usually is not worth the cost for overall contenders to attack on the flat often leads to relatively dull stages. Therefore, race organizers have long been trying to reduce the costs and increase the benefits of attacking on flat stages (Chany and Cazeneuve 2003). For example, in 1936, Tour de France organizers "cut" many stages in two or three parts to multiply stage winners' time bonuses. In 1951, they shortened flat stages and they also modified the calculation of the team general classification. While each team's performance used to be measured by the team's best three riders on the final individual general classification, it was now calculated by the team's best three riders in each stage, thus giving more importance to early, flat stages.

In everyday life, agents have to decide not only what to do but also when to do it. Each of two countries may have to choose when to mobilize their troops or to declare war. Act too early and you will be seen by third parties as the attacker. Act too late and you will have lost the war without even fighting. However, when deciding when to attack, riders may not just have strategic considerations in mind, but normative expectations too (Elster 2009). In cycling, certain norms of etiquette or fairness prohibit riders from attacking when their opponents are having sanitary stops, going through the feed zone or having mechanical problems. It should be noted that an unexpected consequence of the diffusion of two-way radios was that they increased riders' respect of such norms because now riders cannot attack ignoring or pretending to ignore their opponents' situation. Generally, norms and an associated demand for sanctions are easier observed in a close-knit network (Coleman 1998). Professional riders, who ride with each other all year long, form such a type of network. In this context it is no wonder these norms emerged and are to some extent respected. After the 15th stage of the 2011 Tour, when Alberto Contador took hold of Andy Schleck's leader's jersey by attacking him while his chain had come off, not only did Schleck reproach him for such behavior, Contador was also booed by the public and he finally apologized. In the early 20th century, when both professional cyclists and occasional riders rode the Tour or Giro, only professionals respected these norms of etiquette, presumably because only professionals expected to repeatedly interact with each other for a sufficient period of time and could have been punished for infringing them.

3. Cooperation in a breakaway and in the peloton: when to "free ride"?

The discussion of attack timing strategy implicitly assumed that breakaways aim at winning stages while the peloton aims at preventing them from doing so, as if each of these groups acted like an individual advancing his self-interest ("fallacy of composition"). Actually, riders face strategic interactions, collective action problems and under-provision of public goods inside both a breakaway and the peloton (Albert 1991). Once in a breakaway, a rider has to decide to what extent he should draft or shield other breakaway riders from the wind. This leads most breakaway riders to defect, unless they profit from certain favorable circumstances. And once a group of riders establishes a breakaway, each rider in the peloton must decide to what extent he should draft or ride against the wind to close the distance to the breakaway. Riders in the peloton thus find themselves in a situation which is partly similar to that of riders in a breakaway.

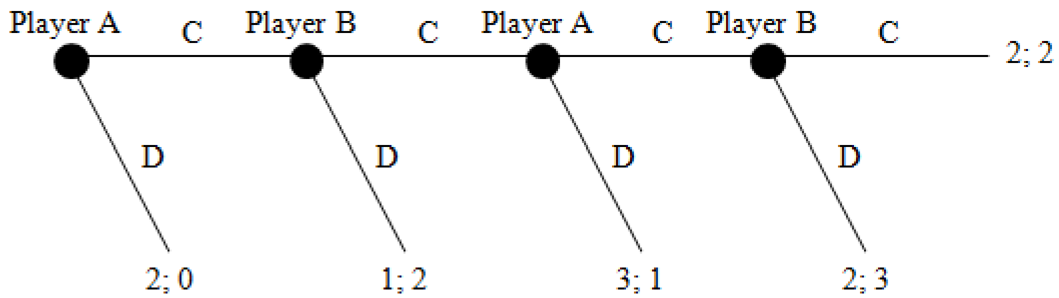
3.1. The breakaway's dilemma: why cooperate in a breakaway?

Once two riders both aiming at the stage win find themselves in a breakaway a few kilometers away from the finish line, they face a highly nerve-racking strategic situation. Each has to choose between starting the sprint first or last, i.e. between attacking or drafting. They also realize that if both refuse to attack, the peloton will likely catch them and they will have wasted energy in breaking away for nothing. Despite this, each is still better off drafting the other until the final meters and beating him on the finish line, so neither is willing to launch the final sprint. This strategic interaction reaches its climax a few hundred meters away from the finish line. Riders "observe" each other and slow down considerably to make each other start the sprint.

When they are further away from the finish line, breakaway riders face a similar, if less acute problem. Each has to choose between riding in the wind or drafting the other rider, or in other words, choose between spending a lot or a little energy while riding in the breakaway. Once again, although both riders realize that if both spend too little energy their breakaway will fail, each will still use any pretext to let the other spend more energy than himself in order to be able to beat him. And given that each rider perfectly knows the other is also trying to spend less energy than he is, all riders tend to draft and their breakaway fails not long after it starts. If ever a rider tried to set an example by taking a long, hard pull at the front of the breakaway, he would sooner or later make it in others' interest to attack because he would now be tired and easy to drop.

The closer the breakaway gets to the finish, the more each rider's reasoning goes as follows: if others do not contribute to the success of the breakaway, there is no reason to unilaterally contribute. And if others contribute, there is still no reason to contribute because unilaterally defecting (called shirking or "free riding") does not substantially reduce the probability that the peloton will catch the breakaway, while increasing substantially the likelihood of beating the other riders at the finish. This is because a cooperator bears the full marginal cost of riding in front, but shares the benefits of increased overall speed with all the other breakaway riders, i.e. riders' rewards are largely independent of their efforts. Thus, when deciding whether or not to cooperate, riders in the breakaway are effectively playing a prisoner's dilemma against each other (or its n-player, sequential version, the "investment game"). More precisely, taking into account the time dimension of a breakaway and modeling it as a sequential, multi-period prisoner's dilemma, breakaway riders are playing a "centipede game" (Rosenthal 1981) where each player has an incentive to be the first to defect (figure 10.1).

Fig. 10.1 Cooperation among breakaway riders as a "Centipede game"



In this "extensive form" game each of two players A and B can alternatively choose either to cooperate (C) or defect (D). The two numbers at the end of each decision node represent first, player A's utility level, and second, player B's utility level. These cardinal payoffs go from 0 (least preferred outcome) to higher numbers (most preferred outcome). Only the first four rounds of the centipede game are shown here.

The "centipede game" is a sequential-move game where two players alternately choose either to pocket a given amount of money (defect), which ends the game, or to hand over that decision to the other player (cooperate), who may in turn hand over the decision to the first player, etc. for 100 rounds. Only the first four rounds are shown in figure 10.1. The twist in this game is that payoffs are structured in a way that if the first player cooperates and the second pockets the money, the first player always wins less than if he had pocketed the money first. As the sum of players' payoffs keeps increasing from each round to the next but does so to the detriment of the decision-maker, by backward induction the first player reasons: at the 100th round the decision-maker will defect because on the last round the decision-maker has no conceivable reason to prefer cooperation. Knowing this at the 99th round the other player will preempt defection because decision-makers always prefer that they decide to defect rather than let the other player defect on the next round. However, knowing this at the 98th round the player will also defect, etc., until in the first round it is in the first player's interest to defect. Backward induction shows that this game has one perfect Nash equilibrium: on the first round, the first player defects, thus ending the game. In a two-rider breakaway, each rider wants to avoid being the last to defect, which means many breakaways stop soon after they start or may never even form in the first place.

In experimental setups, most people playing the centipede game do not defect on the first round. Possibly because the first player may doubt the second player's rationality he cooperates, hoping and believing that the second player will not immediately defect. And because the first player apparently is irrational (he did not defect on the first round), it is in the second player's interest to make the first player believe that he too is irrational. In other terms, if at least one of the players is unsure about the other's rationality (or unsure about the other's belief about his own rationality) both may well cooperate and thus increase their joint gains. However, near the end of the game, as each player starts fearing that the other player will be first to defect, empirically players do defect, thus ending the game before the last possible play. As in experimental centipede games, riders in a breakaway start by cooperating but, near the end of the stage, each starts pre-emptively defecting for fear of becoming the loser. In this sense, riders nicely replicate outside of the usual experimental setup certain end-of-game non-cooperative behavior. However, it is unlikely that riders cooperate for the reason that they doubt each other's rationality. Riders are professionals and each of them knows riders are rational, each also knows riders know riders are rational, etc., which leads them to reason using a higher number of steps of iterated dominance than most people in the lab (around 1.5 or 2 steps (Camerer 2003)). Why, then, do certain breakaways succeed and certain groups of riders break away in the first place?

The Gruppetto's dilemma

An interaction structure which is similar to the breakaway's dilemma is found in the "*gruppetto*" (formerly called the "autobus"), a group of riders in difficulty in hard mountain stages which forms behind the leading peloton to try and reach the stage finish within the time limits. In this group, it is in each rider's interest to draft other riders so as not to blow up. But if each rider drafts and none is willing to ride in front the *gruppetto* will slow down and all its members will be eliminated. However, if failing to finish the stage within the time limits is sufficiently costly to one of the *gruppetto*'s riders, typically the sprinter's jersey holder, he and his teammates will be willing to ride in front of the group and thereby let others draft. Alternatively, because the *gruppetto*'s riders are most often the same and get to know each other well, they can easily identify and punish those riders who avoid riding in front even when they physically could. For instance, the *gruppetto*'s cooperative riders may condition their waiting for a rider and giving him food or energy drinks when he needs it to his usually being cooperative.

3.2. Possible solutions to the breakaway's dilemma: how can certain breakaways succeed?

When breakaway riders form a “latent group” (Olson 1965), i.e. a group with common interests but where everyone prefers to defect no matter what others do, they will not provide the public good (i.e. the breakaway) and the breakaway will sooner or later fail. However, collective action in a breakaway might still be possible in two types of cases.

The members of a “privileged group” (Olson 1965) may include at least one person who values the public good enough to be willing to provide it. In a breakaway, a rider may be willing to ride in front of the group and forgo his chances of winning the stage as long as that makes him gain enough time or points on his competitors. In the 8th stage of the 1973 Tour, José Manuel Fuente was able to ascend the col d’Izoard sitting on leader Luis Ocaña’s wheel because the latter, although furious about working for Fuente (a fellow Spaniard he did not get along with very well), was willing to increase his advance on his general classification competitors. There exist additional private gains to cooperation in breakaways. A prize given to the most combative rider of the stage, (small) prizes along the route for the first riders to cross certain places, and TV time, which is good to a rider both to make a name for himself and to show his sponsor’s logo and thus hopefully extend his employment contract. These “selective incentives” to cooperation might explain why a rider may be better off cooperating unilaterally, which in turn may explain why another rider may be better off cooperating given that at least one other will be cooperating, provoking critical mass and bandwagon effects like those found in the development of strikes, riots and revolutions (Granovetter 1978). Social life too includes such privileged groups. During the Cold War, the United States was so eager to contain Communism that it was willing to pay for the national security of all countries of the North Atlantic Treaty Organization.

The members of an “intermediate group” (Olson 1965) may also perform collective action if the group fulfills two conditions. First, the group must be small enough to enable its members to identify free riders. Professional riders form a small world in which everyone knows who are the free riders (drafters) or the conditional cooperators. Second, the group must expect to be interacting indefinitely (i.e. infinitely or a finite but unknown number of times), so that its members may punish free riders but cannot reason by backward induction and thereby conclude that they had better defect. Riders may indeed expect that they will interact some unknown number of times with other riders, if not in the following stages of the same race at least in coming races or in some of the multiple competitions in which they will participate in their careers. Riders who have a bad reputation typically pay the price. When in the 1919 Tour de France Henri Pélissier had made himself unpopular among the peloton, as soon as he had mechanical problems the peloton attacked. A rider may thus be better off building a reputation of not being a “wheel sucker” or a “rat”, otherwise no other rider will be willing to cooperate in the breakaways in which he finds himself. To build such a reputation, riders must earn it, i.e. they need to prove that they may contribute to collective work in breakaways. In other words, a major reason why some breakaways succeed is because riders cooperate to send all riders a signal that when they will find themselves in the same breakaway they will not be cheated and may cooperate. In the long term, this strategy may well increase conditional cooperators' number of wins, relative to wins by free riders. That is to say, the prospect of indefinite interactions gives riders incentives to cooperate. However, in the most prestigious road races, riders with a strong reputation of being (conditional) cooperators might be especially tempted to use that reputation to free ride and win the most important stage of their career. How may various factors affect a rider's temptation to free ride and a breakaway's risk of failure?

First, when the number of breakaway riders increases, the marginal effect of each rider's effort on the overall speed of the breakaway decreases and each rider's likelihood of winning in case the peloton never catches up decreases, which makes it even more tempting or necessary to free ride. Smaller breakaways thus tend to favor cooperation more. However, it is also true that as the number of breakaway riders increases, the breakaway's physical disadvantage relative to the peloton decreases. And as the number of teams present in the breakaway increases the number of the peloton's teams willing to chase down the breakaway decreases. This increases the likelihood of breakaway success. Hence, which of these opposite-direction effects most impacts a breakaway rider's chance to win the stage, or what is the optimal size of a breakaway, is an open empirical question.

Second, when in a breakaway a rider believes he is not the best sprinter, the cooperation problem worsens. Why would a rider cooperate if he believes he will not win the stage anyway? The best sprinter may promise the other breakaway riders compensation for their cooperation: if you cooperate and I win, we will share the stage win's cash prize. More generally, if one rider profits from the breakaway more than the others, perhaps because he may win the stage and at the same time take hold of one of the leadership jerseys, he may also compensate them for their efforts. In the 13th stage of the 1991 Tour Miguel Indurain, who went on to win the general classification, gave Claudio Chiappucci the stage win to cooperate. However, such deals can be financially profitable only when there are few riders in the breakaway, i.e. when cooperation problems are least acute. In the absence of such side payments, when the chasing peloton closely follows the breakaway, it is the breakaway's best sprinter who has the most incentives to launch the sprint (Dilger and Geyer 2009). Like in a Rubinstein bargaining game where two players alternately make (an unlimited amount of) offers and counteroffers to split some amount of surplus whose size is diminishing over rounds of negotiation, a player's relative impatience disadvantages him in the bargaining process (Binmore et al. 1992). The most impatient rider, i.e. the rider whose likely ranking in the breakaway sprint is most threatened by the peloton's comeback, may be willing to provide the whole breakaway with the public good of launching the sprint, thus making the breakaway a "privileged group".

In other contexts, a rider who knows he is not the breakaway's best sprinter may still be willing to cooperate for some time if he can hope to drop the breakaway's better sprinter before the final sprint and win solo. This is a major reason why certain riders break away in the first place: they hope to first gain some time on the peloton and then attack again to drop other breakaway riders and avoid the stage-finish interaction which is fatal to many breakaways. However, attacking early usually enables the better sprinter to draft the attacker and still win the stage (Dilger and Geyer 2009), except if the attacker can somehow launch a surprise attack. In addition, the better the breakaway riders evaluate each other's probabilities of winning the stage in a sprint or solo, the harder cooperation will be in the breakaway. Why would a rider cooperate if he knows that whatever his strategy he is unlikely to win? Only when each breakaway rider believes he is the better sprinter will they all start sprinting late, as in individual track sprint. Otherwise, the riders who know they are the worst sprinters will try to drop other breakaway riders before the final sprint. For a rider, this strategy is particularly attractive when the other riders left in the breakaway have cooperation problems, i.e. when none of them is still willing to lead the breakaway for fear of letting others draft and win.

Third, when a breakaway contains at least three riders and at least two (but not all) of them are from the same team, cooperation problems change. In such cases, teammates' strategy may consist for one of them in doing all the work and sacrificing his own chances of a win to increase the chances of his teammate to win. Teammates' strategy may also consist for one of them in attacking little before the finish and forcing the other riders to try and catch up on him, enabling his teammate to draft them and win. Anticipating this, riders who are not from their team will not cooperate in the first place. This became very clear in the 2015 edition of Omloop Het Nieuwsblad. British rider Ian Stannard from the *Sky* team found himself in a break with three riders from the *Etixx* - *Quick Step* team, amongst them their team leader Tom Boonen who desperately wanted to win this race. Stannard drafted the three other riders for about 40 kilometers and when the teammates started attacking little before the finish he turned out to be fresher rider of the breakaway. He was able to counter every attack and finally outsprinted Niki Terpstra, the only *Etixx – Quick Step* rider that was strong enough to hold the wheel of Stannard when he attacked himself with three kilometers to go.

3.3. The peloton's dilemma: why cooperate in the peloton?

Once a group of riders has broken away, it is the peloton's rider who has the most to lose from the breakaway's time gain, usually the leader, who asks his domestiques to chase down the breakaway. When this happens, in the early part of a stage, the peloton's riders may free ride on the leader's team's efforts and the peloton forms a "privileged group." In the later part of the stage, when the breakaway's time gain has been "controlled" by the leader's team but the breakaway may still win the stage, the riders who have the most to lose from the breakaway's success are the best sprinters. It is now up to them to ask their teammates to catch the breakaway before the final sprint. This involves two kinds of strategic considerations.

First, teams with sprinters are better off catching the breakaway at the optimal time: early enough so that no breakaway rider wins the stage, but late enough so that once the breakaway is caught there is too little time left for other riders to counter-attack. To determine at which speed it should go, for a long time a sprinter's team used "*Chapatte's law*", the empirical pattern according to which in flat stages a chasing peloton can take back 1 minute every 10 kilometers on a solo or small group breakaway. However, strategic interactions inside the breakaway or between the breakaway and the peloton may make it difficult for teams to anticipate and adjust their speed to catch up to the breakaway at the optimal time. Indeed, more recently breakaway riders have learned to save their energy early in the race. Instead of trying to widen the time gap as much as possible, as was common in the old days, nowadays once breakaway riders have created a sufficiently large time gap (e.g. 5 minutes), they adjust their pace to that of the peloton to keep their advance stable while saving as much energy as possible. Such a strategy makes it much harder for teams to catch a breakaway right before the stage finish.

Second, although teams with top sprinters are better off mutually cooperating to increase their joint chances of catching up on the breakaway, each team would prefer to let the others do the chasing work and still have their leader win. If the best sprinter's team can consistently catch breakaways and win sprints so that its payoff expectancy of chasing (which could, theoretically, be computed as the probability of catching up on the breakaway times the probability of winning the sprint times the stage prize less the chasing costs) is always positive, it may be willing to do all the chasing work on its own. In this case, other sprinters' teams will be able to free ride on these efforts and still win a certain amount of stages. However, when no team is strong enough to make the others a privileged group, it may be in sprinters' teams' collective, long-term interest to strike deals. The stronger teams pay some weaker teams or let them win a certain number of stages to contribute to chasing. Empirical information on the results of bargaining among sprinters' teams is hard to find, though.

4. Three-player interactions: with whom to ally?

A coalition is a group of players who coordinate their actions for their mutual benefit, usually to the detriment of some other group of players. Coalitions may be hard to build, though, as in the three-player split-the-dollar game (Friedman 1990). When a group of three players is given 1 dollar (or, for that matter, 99 cents) as long as at least two players agree on any division of this sum among them, all the three-player coalitions that may emerge (e.g. 33; 33; 33) are dominated by two-player coalitions (e.g. 50; 50; 0) and all two-player coalitions are dominated by other two-player coalitions (e.g. 51; 0; 49). Rational players may thus find it hard to build a coalition in the first place. Nevertheless, a duel among three opponents (sometimes also called *truel*) may take several forms (McCain 2010).

The most common interaction is when two riders coalesce against a third rider who is left out of the coalition. Two riders R_1 and R_2 typically draft each other to drop, chase down or otherwise gain time on an opponent O. One particularly tricky situation for O is when R_1 breaks away. If O does not chase R_1 or is unsuccessful then R_1 will win the stage. But if O successfully chases he will unwillingly allow R_2 to draft him so R_2 will beat him at the finish. Knowing this in advance can only demotivate O. In the 19th stage of the 1950 Tour, French teammates Louison Bobet and Raphaël Géminiani broke away together. After a few minutes Bobet accelerated again while Géminiani waited for Bobet's opponents, notably Ferdi Kübler, who now had the choice either not to chase and let Bobet take hold of the leader's jersey or to chase him but in the process let Géminiani draft him and enable him to win the stage. Kübler was finally able to go back on Bobet but predictably Géminiani counter-attacked and won the stage. In the penultimate stage of the 1984 Vuelta, Caritoux was the leader, Fernández was second and Delgado third. Delgado broke away: "*Momentarily, Caritoux's lead was in danger. Beside him was Alberto Fernández, second overall and just thirty-seven seconds in arrears. Chase and risk being jumped by Fernández, don't chase and hand victory to Delgado, those were Caritoux's options. Then the Italians came to the rescue, in the form of Francesco Moser […] and Simone Masciarelli. Delgado was recaptured, Caritoux stayed in the maillot amarillo and José Recio won the stage into Segovia*" (McKay 2012). By contrast, in the 1985 Vuelta, the leader David Millar was in a group with second-placed Pacho Rodríguez and third-placed Ruiz Cabestany (and several other riders). Pedro Delgado, who could take the first place, had attacked and was gaining time on them all. This put Millar into a terrible situation: do not chase and let Delgado win, chase and enable Rodríguez to gain time in the final kilometers. Finally, Millar lost his first place to Delgado with Rodríguez's consent, a sign of national unity among Spanish cyclists. Similarly, in the 1990 Tour, Greg LeMond profited from the fact that his teammate Ronan Pensec took hold of the leader's jersey on the 10^{th} stage. If rival teams wanted to gain time on Pensec they had to attack, which enabled LeMond to draft them.

Another tricky situation for O is if he breaks away with $R_{1,}$ who is allied to R_2. If O does not lead the breakaway he will not be able to gain time on R_2. But if O does all the work in the breakaway R_1 will draft him and win the stage. In the 17^{th} stage of the 1986 Tour, when runner-up Greg LeMond broke away with third-placed Urs Zimmermann, there was a risk that LeMond's teammate Bernard Hinault would lose not only his leader's jersey to LeMond, but also his virtual second place to Zimmermann. As this was not in Lemond's team's interest, when Zimmermann threatened Hinault's second place, LeMond was content with drafting him for the remainder of the stage.

Another interesting fight among three opponents is when two riders compete against each other for the favors of a "spoiler," a third rider who cannot win but can still decide who among the other two will. When two teams compete to get help from a third team and the helping team can choose the winner, the helping team might be able to reap almost all the benefits from its help. One way for the spoiler to help a team might be to backstab the other. In the 1906 Milan-San Remo, "*Giovanni Gerbi, after two hundred kilometers on his own, was caught in the closing kilometers […] by Gustave Garrigou. Knowing that Garrigou had the beating of him in a sprint, and knowing that his own Bianchi team-mate, Lucien Petit-Breton, was closing on the pair of them, Gerbi slowed things down at the front and then, with Petit-Breton on board and the three racing for the line, pushed Garrigou off his bicycle and sealed the victory for Petit-Breton. […] Having worked out he couldn't beat Garrigou, Gerbi did some mental arithmetic. Bianchi were paying him two-and-half lire a kilometer if he won the race. But they were paying Petit-Breton six times as much if he won the race. Gerbi did a deal — fifty-fifty — and did the deed. He lost the race but pocketed more than he would have had he won*" (McKay 2011).

5. Sprint strategy: how to sprint?

When at the end of a race all the peloton's riders or several breakaway riders arrive together at the finish line, the best sprinter will usually be able to win the stage. Although sprints imply a considerable amount of force, they also have to do with strategy, not only to decide when to start a sprint but also how to behave while sprinting.

Let us imagine that a rider L leads out a sprint and following him are sprinters F_1 and F_2. While F_1 is behind L to his left, F_2 is behind L to his right and both are at the same distance from both L and the finish line. In this situation both F_1 and F_2 can either draft L (which is what both prefer to do) or stay in line and forgo drafting L. If only F_1 drafts, he wins and F_2 loses, and vice versa. If both F_1 and F_2 stay in line, none drafts so L wins. And if both F_1 and F_2 try to draft L they collide and crash at more than 40 mph and must quit the race. Although both riders prefer they both forgo drafting rather than both draft, each also prefers even more to be the only one drafting. This interaction between sprinters has the structure of a "game of chicken" (table 10.2).

Table 10.2 Sprint as a "Game of chicken"

		Sprinter F_2	
		Forgo draft	Draft
Sprinter F_1	Forgo draft	2 ; 2	1 ; 4
	Draft	4 ; 1	0 ; 0

The game of chicken is an anti-coordination bargaining game with two Nash equilibria: unilateral defection and unilateral cooperation. In table 10.2 this corresponds with the upper-right and lower-left cells, i.e. the two situations in which one of the sprinters drafts and the other one forgoes drafting. As Schelling (quoted in Dixit and Nalebuff 2008) asked: "*when two trucks carrying dynamite meet on a single-lane road, who backs up?*" Like in the 1962 Cuban missile crisis, the outcome of the game may depend on players' capacity to use brinkmanship to impose their will. And to make the threat of "mutually assured destruction" credible even while each player is better off being accommodating if the other is inflexible, each player might try to appear as mad and unpredictable, as Nikita Khrushchev and later Richard Nixon did, during Cold War negotiations. Sprinters indeed try to build intimidating reputations for reckless people who will not give in whatever the costs to them or to others. As in the "flexible response" doctrine of nuclear deterrence, a sprinter may gradually get closer to the sprint leader's slipstream or block another sprinter on the side of the road, fight for position and spread his elbows to frighten and get the better of a rival. In the final sprint of the 1988 World Championship, Steve Bauer elbowed Claude Criquielion and made him fall. In the sprint of the 6th stage of the 1997 Tour, Tom Steels threw a bottle at another sprinter (Frédéric Moncassin) and in the sprint of the 11th stage of the 2010 Tour, Mark Renshaw head-butted another sprinter (Julian Dean). Both were eliminated for such behavior, but it is not clear whether these behaviors cost them or helped them build a tough reputation of sprinters one should not challenge.

Conclusion

Strategic interactions of riders have the same logical structure as many social interactions. Among the multiple games within the larger game of bicycle races are: games between two individuals (riders) or organizations (teams), but also games among three or more players, which allow coalitions to develop; games that are constant-sum or variable-sum, thus involving partly conflicting interests but also potentially mutually beneficial cooperation; games that are simultaneous or sequential, thus allowing players to (mis)trust each other and be (dis)loyal; and games that involve complete or incomplete information, allowing players to screen others, signal their unobservable characteristics or bluff. Part of the reason why cycling is fun to watch is precisely because it is cognitively and emotionally a lot like social life itself, including relations between spouses, friends, neighbors, club members, workmates, consumers, taxpayers or organizations such as firms, trade unions, cartels or states. From interpersonal to international relations, the strategic interactions between all these agents have much in common, and in this sense studying professional road cycling helps to better understand social life.

The mentioned game-theoretical models of bicycle races may be tested empirically to explain statistical regularities across time or races, not just punctual or anecdotal events. "Mechanism design" and "tournament theory" may also be used to establish "incentive compatible" rules and otherwise help race organizers maximize competition between teams, outcome uncertainty and the quality of the show.

References

- Albert E (1991) Riding a Line: Competition and Cooperation in the Sport of Bicycle Racing. Sociology of Sport Journal 8: 341-361
- Aumann R, & Hart S (eds) (2002) Handbook of Game Theory with Economic Applications. Elsevier, Amsterdam
- Binmore K, Osborne M, & Rubinstein A (1992) Noncooperative Models of Bargaining. In: Aumann R, Hart S (eds) Handbook of Game Theory with Economic Applications, vol. 1. Elsevier, Amsterdam, p 179-225
- Camerer C (2003) Behavioral Game Theory: Experiments in Strategic Interaction. Princeton University Press, Princeton
- Candelon B, & Dupuy A (2010) Hierarchical Organization and Inequality in an Economy with an Implicit Market for Productive Time. IZA Discussion Paper. Available via http://ftp.iza.org/dp5391.pdf. Accessed 1 March 2014
- Chany P, & Cazeneuve T (2003) La fabuleuse histoire du Tour de France. Minerva, Geneva
- Chany P, & Penot C (1997) La fabuleuse histoire du cyclisme. La Martinière, Paris
- Chiappori P-A, Levitt S, & Groseclose T (2002) Testing Mixed-Strategy Equilibria When Players Are Heterogeneous: The Case of Penalty Kicks in Soccer. The American Economic Review 92:1138-1151
- Coleman J (1998) Foundations of Social Theory. Harvard University Press, Harvard

- Dilger A, & Geyer H (2009) The Dynamic of Bicycle Finals: A Theoretical and Empirical Analysis of Slipstreaming. Economic Analysis and Policy 39:429-442
- Dixit A, & Nalebuff B (2008) The Art of Strategy. A Game Theorist's Guide to Success in Business and Life. W. W. Norton and Company, New York
- Elster J (2009) Norms. In: Hedström P, Bearman P (eds) The Oxford Handbook of Analytical Sociology. Oxford University Press, Oxford, p 195-217
- Fallon L, & Bell A (2013) Viva la Vuelta ! 1935-2013. Mousehold Press, Norwich
- Fournel P (2012) Anquetil tout seul. Le Seuil, Paris
- Friedman D (1990) Price Theory: An Intermediate Text. South-Western Publishing Co., Nashville
- Granovetter M (1978) Threshold Models of Collective Behavior. American Journal of Sociology 83:1420-1443.
- Harper D (2012) Chess On Wheels: Why Cavendish Didn't Win the Olympic Road Race. Sabotage Times
- Kollock P (1998) Social Dilemmas: The Anatomy of Cooperation. Annual Review of Sociology 24:183-214
- Larson, D., & Maxcy, J. (2013). The industrial organizational of coaching: Cycling as clarifying evidence. Journal of Sport Management , 27(5), 363-378.
- Larson, D., & Maxcy, J. (2014). Uncertainty of outcome and radio policy in professional road cycling. Journal of Sport Management, 28(3), 311-323.
- McCain R (2010) Game Theory: A Nontechnical Introduction to the Analysis of Strategy. World Scientific Publishing Company, London
- McGann B, & McGann C (2012) The Story of the Giro d'Italia. A Year-By-Year History of the Tour of Italy. Volume Two: 1971-2011. McGann Publishing, Cherokee Village.
- McGann B, & McGann C (2011) The Story of the Giro d'Italia. A Year-By-Year History of the Tour of Italy. Volume One: 1909-1970. McGann Publishing, Cherokee Village
- McGann C, & McGann B (2008) The Story of the Tour de France vol. 2. Dog Ear Publishing, Indianapolis
- McGann C, & McGann B (2006) The Story of the Tour de France vol. 1. Dog Ear Publishing, Indianapolis
- McKay F (2012) Dirty Deals Done Dirt Cheap. In: Podium Cafe. Available via http://www.podiumcafe.com/2011/5/11/2162334/VueltaAEspana1985. Accessed 1 March 2014
- McKay F (2011) Maglia Rosa, by Herbie Sykes. In: Podium Cafe. Available via http://www.podiumcafe.com/2011/5/3/2150874/MagliaRosa. Accessed 1 March 2014
- Olds T (1998) The Mathematics of Breaking Away and Chasing in Cycling. European Journal of Applied Physiology 77:492-497
- Olson M (1965) The Logic of Collective Action: Public Goods and the Theory of Groups. Harvard University Press, Harvard
- Palacios-Huerta I (2003) Professionals Play Minimax. Review of Economic Studies 70:395-415
- Parlebas P (2005) Modeling in Games and Sports. Mathematics and Social Sciences 170:11-45
- Polak B (2008) Open Yale Courses. Econ 159: Game Theory. Available via http://www.youtube.com/watch?v=nM3rTU927io&list=SP6EF60E1027E1A10B&index=1. Accessed 1 March 2014
- Prinz J, & Wicker P (2012) Team and Individual Performance in the Tour de France. Team Performance Management 18:418-432
- Rogge N, Van Reeth D, & Van Puyenbroeck T (2013) Performance Evaluation of Tour de France Cycling Teams Using Data Envelopment Analysis. International Journal of Sport Finance 8:236-257
- Rosenthal R (1981) Games of Perfect Information, Predatory Pricing, and the Chain Store. Journal of Economic Theory 25:92-100
- Thompson C (2003) René Vietto et le Tour de France 1934. Un sacrifice héroïque ou un héros sacrifié ? Histoire et sociétés 7:35-46
- Van Reeth D (2013) TV Demand for the Tour de France: the Importance of Stage Characteristics Versus Outcome Uncertainty, Patriotism and Doping. International Journal of Sport Finance 39-60

- Walker M, & Wooders J (2001) Minimax Play at Wimbledon. The American Economic Review 91:1521-1538